and soil-water dilution could have resulted in a reduction of osmotic potential, thus contributing to some of the observed reduction in growth. Further studies will be required to determine whether a reduction in root hairs or a change in osmotic potential could alter nutrient and water fluxes into wheat plants sufficiently to account for the observed differences in plant growth.

Root excision and defoliation studies indicate that compensatory development of an organ(s) tends to restore the original ratio (e.g., shoot to root), unless external or internal factors prevent it (Brouwer and deWit, 1969; Crossett et al., 1975). Although external factors known to affect coordinated growth can be controlled, the roots themselves can markedly influence the activities of the shoot (Torrey, 1976), thus affecting coordinated growth. Root-derived growth substances are known to affect shoot growth, including the outgrowth of lateral shoots (Skene, 1975). Although applications of exogenous growth regulators partially restored shoot growth of bean plants, growth restrictions of entire plants could not completely be overcome by any hormonal treatment tested (Carmi and Heuer, 1981). Our results with wheat demonstrate that limiting the space available for root growth and development can limit coordinated growth of the whole plant even when water and minerals are adequate. Whether this specific limitation of the root system in wheat restricts shoot growth through some hormonal system as proposed by Carmi and Heuer (1981) for bean plants remains to be elucidated.

ACKNOWLEDGMENTS

The authors gratefully acknowledge technical assistance from Mary Herrington Zuzel and chemical analyses performed by Paul Rasmussen and the Auburn University Soil Testing Laboratory.

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CANOPY TARGET DIMENSIONS FOR INFRARED THERMOMETRY[1]

J. C. O'TOOLE AND J. REAL[2]

Abstract

The increasing use of infrared thermometry in agricultural research and management obviates the necessity of users being cognizant of the instrument's target area characteristics. In this note, we illustrate the target dimensions when an infrared thermometer of specified field of view (4°, 8°, and 20°) is used to remotely sense surface temperature of a leaf, canopy, or crop surface. Knowledge of target dimensions and special characteristics related to the ellipse center and target point at various distances to and angles above the target surface should decrease error in surface temperature measurements and assist in standardization of techniques.

Additional index words: **Remote sensing, Canopy temperature.**

THE use of handheld instruments to remotely measure the surface temperature of leaves, foliage, canopy, and crops has numerous applications in agricultural research and management: studies on crop energy balance (Jackson et al., 1981); irrigation timing and estimates of evapotranspiration (Clawson and Blad, 1982; Hatfield et al., 1983) and selection of breeding lines for water use characteristics (Mtui et al., 1981) and response to water deficits (Blum, 1980).

Routine use of the handheld infrared thermometer (IRT) to accurately measure the leaf, foliage, canopy, or crop temperature requires that the user be able to estimate target dimensions based on the position of the sensor in relation to the surface being remotely sensed (Fig. 1). This note illustrates how the field of view (FOV) of the infrared thermometer, distance to the target and viewing angle affect the shape and area of the target. We realize that the actual sensor in currently available commercial units is more rectangular than circular but have proceeded in this note with the assumption that the target dimensions are most conservatively estimated assuming the FOV is a solid angle.

The field of view of the IRT forms a right circular cone when it is held perpendicular to a surface. The view area is a circle of radius given by the following relationship.

$$r = f \tan\frac{FOV}{2},$$

where r = radius of the circle, f = distance of the view area from the instrument, FOV = field of view solid angle (Jackson et al., 1980).

Imaginary lines of sight lying on the outermost portion of this right circular cone are called generators of

[1] Contribution from the Agronomy Dep., Int. Rice Res. Inst., Los Baños, Laguna (mail address: P.O. Box 933, Manila), Philippines. Received 8 Sept. 1983. Published in *Agron. J.* 76:863–865.
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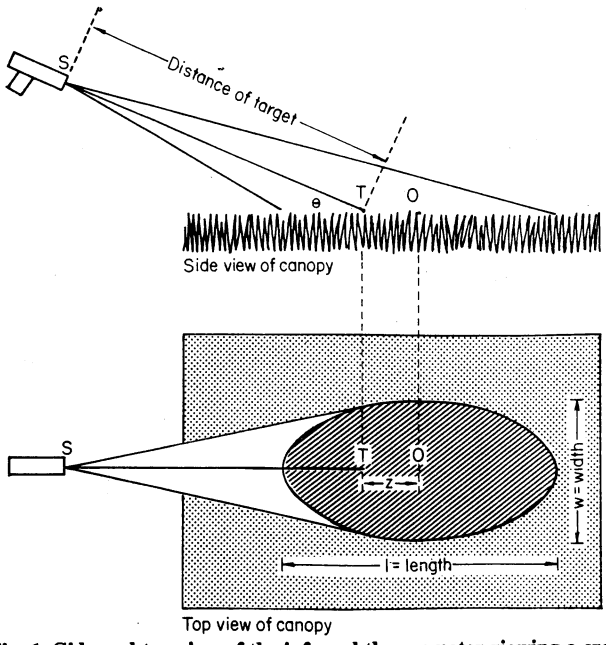

Fig. 1. Side and top view of the infrared thermometer viewing a crop canopy surface at a variable distance from the sensor (S) to the target point (T) and at a variable angle (θ) above horizontal with reference to the canopy height. The elliptical target area is described by its length (l) and width (w). Note the target point (T) is offset from the ellipse center by distance Z.

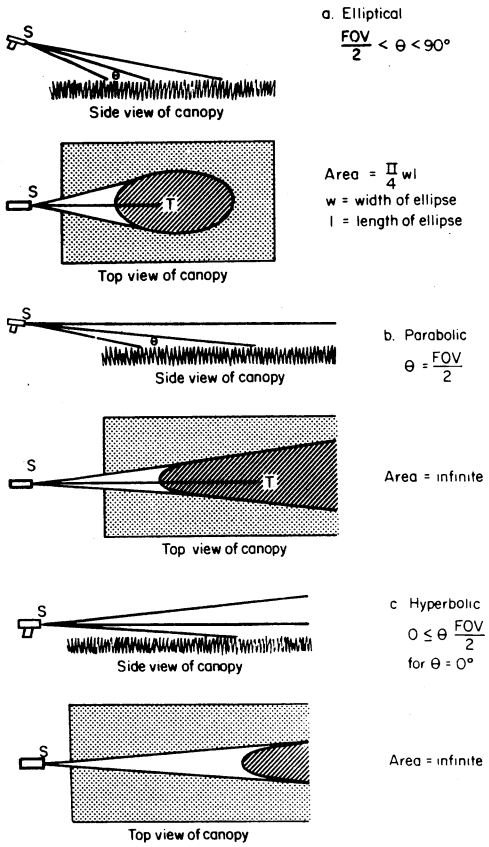

Fig. 2. Relationship between the infrared thermometer position (angle above horizontal) in relation to the canopy surface for three different conic sections a) elliptical, b) parabolic, and c) hyperbolic. Field of view is the instrument field of view, S is the sensor, θ is the view angle above the crop surface, and T is the target point.

the cone and they pass through the vertex S. The curves of the intersection of a plane and a right circular cone are known as conic sections. A conic section is the curve in which a plane cuts a right circular cone. When the IRT is held at a given angle above the horizontal

Table 1. The effect of distance to and viewing angle above the target surface on the dimensions of the elliptical area being remotely sensed. The three field of view (FOV) cases illustrated (4°, 8°, and 20°) are characteristic of currently available infrared thermometers.

Distance of target	Area length width offset	Viewing angle above the target surface			
		10°	20°	30°	40°
FOV = 4°					
0.50 m	A	0.006	0.003	0.002	0.002
	L	0.209	0.103	0.070	0.054
	W	0.036	0.035	0.035	0.035
	Z	0.021	0.005	0.002	0.011
1.00 m	A	0.023	0.011	0.008	0.006
	L	0.419	0.206	0.140	0.109
	W	0.071	0.070	0.070	0.070
	Z	0.042	0.010	0.004	0.002
2.00 m	A	0.094	0.045	0.031	0.024
	L	0.837	0.412	0.280	0.218
	W	0.143	0.140	0.140	0.140
	Z	0.083	0.020	0.009	0.005
3.00 m	A	0.211	0.102	0.069	0.054
	L	1.256	0.618	0.421	0.327
	W	0.214	0.211	0.210	0.210
	Z	0.124	0.030	0.013	0.007
4.00 m	A	0.375	0.182	0.123	0.096
	L	1.675	0.824	0.561	0.435
	W	0.285	0.281	0.280	0.280
	Z	0.166	0.040	0.017	0.009
FOV = 8°					
0.50 m	A	0.029	0.012	0.008	0.006
	L	0.478	0.212	0.142	0.110
	W	0.076	0.071	0.070	0.070
	Z	0.095	0.020	0.009	0.005
1.00 m	A	0.114	0.048	0.031	0.024
	L	0.956	0.425	0.284	0.219
	W	0.152	0.143	0.141	0.140
	Z	0.190	0.041	0.017	0.009
2.00 m	A	0.457	0.190	0.126	0.097
	L	1.911	0.849	0.568	0.438
	W	0.305	0.285	0.282	0.281
	Z	0.379	0.082	0.034	0.018
3.00 m	A	1.029	0.428	0.283	0.217
	L	2.867	1.274	0.852	0.657
	W	0.457	0.428	0.423	0.421
	Z	0.569	0.122	0.052	0.027
4.00 m	A	1.830	0.760	0.503	0.386
	L	3.823	1.698	1.136	0.876
	W	0.609	0.570	0.564	0.561
	Z	0.758	0.163	0.069	0.037
FOV = 20°					
0.50 m	A	∞	0.107	0.057	0.041
	L	∞	0.674	0.389	0.287
	W	--	0.202	0.185	0.180
	Z	--	0.163	0.059	0.030
1.00 m	A	∞	0.427	0.226	0.163
	L	∞	1.347	0.779	0.574
	W	--	0.403	0.370	0.361
	Z	--	0.326	0.119	0.060
2.00 m	A	∞	1.706	0.905	0.650
	L	∞	2.695	1.556	1.148
	W	--	0.806	0.741	0.721
	Z	--	0.653	0.238	0.121
3.00 m	A	∞	3.839	2.036	1.464
	L	∞	4.042	2.334	1.722
	W	--	1.209	1.111	1.082
	Z	--	0.979	0.356	0.181
4.00 m	A	∞	6.825	3.620	2.602
	L	∞	5.388	3.111	2.296
	W	--	1.613	1.481	1.443
	Z	--	1.305	0.475	0.241

over a plant canopy (assumed flat), the view area on that canopy assumes one of three particular conic sections: ellipse; parabola; and hyperbola (Fig. 2). When the angle θ is small resulting in a parabolic or hyperbolic conic section the sensor field of view extends past the desired target or plot canopy surface area. This condition leads to errors in surface temperature measurement by including in the sensor's view adjacent canopy or soil area outside the desired target in the first case and cool sky area in the second case. Orientation of the sensor so that an elliptical conic section cuts the canopy surface plane and its length and width are confined to the plot desired is the optimal relationship.

When $\theta = 90°$, the view area is a circle, a special form of ellipse when $w = l$. In the case where FOV/$2 < \theta < 90°$, for a constant target distance f, at greater angles, the elliptical shape tends to become circular and the area smaller.

At smaller angles and constant target distance f, the area becomes larger. In addition to θ, the distance to the target point also affects the ellipse dimensions. If the instrument is held further from T, the target point, while keeping θ constant, the view area becomes progressively larger by the relationship that the target area is proportional to the square of the distance to the target. Incorrect estimation of the ellipse area with increasing distance to the target point may result in systematic errors especially when the IRT is used to monitor surface temperature of small plots.

The derivation of the formulae for an elliptical view area with varying target angle (θ), target distance (f), and IRT field of view was obtained using Kells and Stotz (1949) and Purcell (1978)[3]. Table 1 illustrates the change in target dimensions and ellipse area being sensed when the IRT is held at various combinations of distance from and angle to the target. It should be noted in Fig. 1 that the target point aimed at is not the center of the ellipse being remotely sensed but is offset from the ellipse center by a distance Z. Table 1 gives the ellipse area, length, width, and distance Z for IRTs with 4°, 8°, and 20° FOV. As the instrument FOV increases the user's knowledge of Z becomes more important in accurately sensing the desired target surface temperature. For additional information on the effects of angle to the target on canopy surface temperature measurement see Kimes (1980).

[3] Full details of the formulae derivation with complete illustrations may be obtained upon request from the authors.

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LETTERS TO THE EDITOR

Dear Editor,
RE: SUNFLOWER POPULATION[1]

My letter (6) in response to Dr. Prunty's article on sunflower population (3) was confined to correcting an incorrect statement of fact (We did not use the head method described in his article) and correcting a misleading statement about our results (8 of our 12 experiments did not support his hypothesis). Dr. Prunty initiated more controversy in his latest article (4) to which I will respond. He now calls the head method the "100% stand" method, but continues to link our "100% stand" method and his "100% stand" method which are not the same as indicated in my letter (6). His "100% stand" method (3, 9) is potentially biased because judgment is involved in selecting heads for harvest. Consequently, his area method is better than *his* "100% stand" method.

Dr. Prunty used his *area* method to establish and harvest plant population densities at two locations (4). Yield differences among populations were not significant in either trial, but he gave neither coefficient of variation (CV) nor least significant difference (LSD) values. Consequently, the reader is uninformed of the variability, and cannot evaluate whether or not the data were too variable to justify a conclusion on population effect. However, he chose one location and calculated what the yields would have been if corrected to 100% stand, and these amounted to 190, 197, 204, and 205 g m^{-2} from 3.8, 5.0, 6.1, and 7.3 plants m^{-2}, respectively. He used this calculation to support his hypothesis that the "100% stand" method is biased because yield increased with population increases. I chose the other location and from his Table 1 and Fig. 1 calculated yields of 244, 241, 248, and 252 g m^{-2} from 5.0, 6.1, 7.5, and 9.1 plants m^{-2}, respectively. These small differences in nonsignificant data at both locations are not valid support of his hypothesis. However, these calculations are agronomically invalid because they ignore reduced plant competition! Loss of stand during the growth of the crop may be partially or fully offset by increased production from the remaining plants (2). Furthermore, the lowest population at both locations was adequate for maximum yield, so mathematically adding yields from nonexistent heads should increase calculated yields in direct proportion to the proportion of missing heads.

I do not know why our article (8) on uniformity of plant spacing was discussed. Despite its title, Dr. Prunty's paper (4) presented no data on how either soil water or plant population influence *uniformity of stand.* However, the second paragraph on p. 748 starts with two sentences about our research and the third sentence starts with, "This work shows. . . ." It should be corrected to, "My (Prunty's) work shows. . . ."

[1] Contribution from the Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, St. Paul, MN 55108. Paper no. 13,810 of the scientific journal series, Minnesota Agric. Exp. Stn. Received 27 Feb. 1984. Published in *Agron J.* 76:865–866.

Scheduler charts plant stress

BRONSON GARDNER

The Leading EDGE

Irrigation has traditionally been scheduled according to factors that do not include plant measurements. Since the early 1970s, the USDA, as well as several universities have been developing a crop water stress index (CWSI). This index is based on the principle that a surface which is evaporating water is cooler (under the same ambient conditions) than a similar non-evaporating surface. Hence, the rate of water evaporation from a leaf surface modifies plant temperatures. Thus, it is possible to define an index which directly responds to the transpiration rate of a leaf. This index also serves as an indicator of plant stress status.

The Stress Index

The stress index in the Schedule® is:

$$\text{Index} = 10^{*}\frac{(TC - TA - Min)}{Max - Min} = 1 - \frac{ET}{ET_p} \quad \text{Eq. (1)}$$

ET is the actual transpiration rate. ET_p is the potential transpiration rate. Min is the minimum temperature a rapidly transpiring plant can achieve under a given set of environmental conditions. Max is the temperature a maximally stressed plant can achieve under a given set of environmental conditions.

Max and min are computed from proprietary algorithms. The theoretical range of the index is 0-10 for a given crop. In actual practice in the field, observed values range between -3 and $+13$.

To compute the index, it is best to simultaneously measure four parameters: canopy temperature, ambient air temperature, relative humidity and solar radiation.

The *Scheduler* can measure each parameter 4 times per second. Up to 55 samples can be collected per data "burst". A burst of 55 samples requires 12-15 seconds to collect the data, with an additional 2-3 minutes calculating time. Up to 18 "bursts" can be included in a set of field averages.

Several software options are available (Table 1).

Scheduler Research

The technology on which the Scheduler is based began as far back as 1842. Since that time, the ability of researchers to measure plant temperatures has progressed from cumbersome thermocouple systems requiring ice baths to battery powered hand-held infrared thermometers. A large volume of information now exists which shows that moisture stress causes elevated plant temperatures relative to healthy plants.

TABLE 1. Scheduler Software Features

General

- Easy to use. Only eight buttons to push (ON/OFF, HELP, PRINT, DEL, ENTER, UP, CALC, DOWN). No computer experience needed.
- Seven pre-programmed crops per unit.
- RS-232 compatible for down-loading to external computers and printers.
- Easily replaced EPROM's for changing between software programs. (Currently this change is made for the user only by our technicians).
- Modem communication for easily changing crops and their associated baselines.
- Real-time clock.
- Battery test features.
- Visual display of the difference between crop and air temperatures.
- Sunlight level feature to automatically delete any data collected at less than 65% full sunlight. The user can enable or disable this feature at will.

Production Software

- 15-day data storage for stress index values for each of 30 separate fields or locations.
- Graphical display of the stress index trends for the most recent 15 days for each of 30 fields. This allows rapid in-field decisions without using an external computer.
- One-day storage of mean values of crop, temperature, air temperature, relative humidity, solar radiation and the stress index. Also stores the time, date and number of samples associated with each average. Means are automatically deleted at midnight.

R&D Software Features

- One day data storage for average values of crop temperature, air temperature, relative humidity, solar radiation and the stress index for 240 separate fields. Standard deviation of crop temperature, vapor pressure deficit, date, time, field number, crop name, and number of samples collected with each average. No data is deleted automatically.
- Ability to transmit all data in real-time to an external RS-232 device, making it possible to capture all the data observed by the Scheduler®.

Additional software applications programs are being developed.

Since the early 1970s, the USDA has been developing procedures which quantify the systematic relationship of leaf temperatures to environmental parameters such as relative humidity, air temperature and solar radiation. Many different universities have joined in that effort.

In 1984, Standard Oil began developing a commercial version of this technology. Nationwide testing was conducted on corn in 1985 using a prototype model. This test showed that the technology could be made in a form acceptable to growers and that the cost/benefit ratio could justify its purchase.

A second model was built in 1986 which incorporated the lessons of 1985. These models were made commercially available and were also installed on a number of research projects. Although many crops had been researched by others using stress index theory, the decision was made to validate existing baselines and develop new baselines for crops that had not been researched. This effort resulted in an extensive data base and the discovery of calculation procedures which enhanced the stability of the index in cool and humid regions. Research is continuing on improved calculation procedures.

The lessons of 1984-1986 were incorporated into the 1987 model, resulting in a technically accurate, easy-to-use instrument which provides a great deal of information about plant stress status.

How to Interpret the Stress Index

Several interpretive techniques are being used with the *Scheduler* stress index:

Photo by Wines & Vines

Bronson Gardner with the Scheduler at a Fresno news conference.

Technique 1 – Threshold Values: With this technique, a user measures the stress index of a crop with the *Scheduler* whenever it is convenient. If the index exceeds a threshold value (usually some constant value the user determines), then the user concludes that stress has begun. As long as a crop canopy stays relatively unchanged between irrigation cycles and the crop does not undergo any radical physiological change, such as rapid leaf expansion, this approach works well. This approach requires some modification if used during a period of rapid crop development, since the relative influence of soil (ground cover) and crop structure on indicated temperatures may change the normal index reading. For example, higher index readings on young healthy cotton than on a mature healthy cotton would be normal.

Technique 2 – Relative Values: With this technique, a user does not consider the past behavior of the index or its absolute value. He is interested in relative differences between areas. As long as a user has an area which he can use as a healthy reference with a high degree of confidence, this approach is very satisfactory. Index differences of 2-3 between an area and a healthy reference area usually indicate the need for irrigation. This approach works well on large operations where is is generally easy to find a recently-irrigated area.

Technique 3 – Seasonal Trends: This technique presumes that a user has a data

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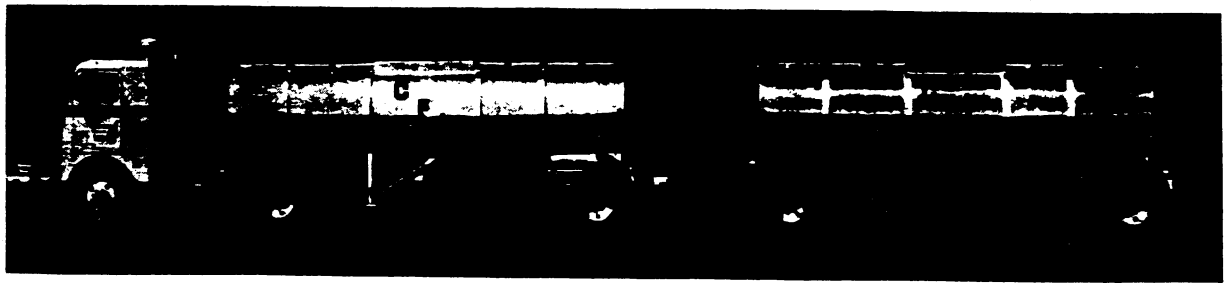

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TABLE 2. Scheduler Hardware Features

- Aspirated air temperature and humidity sensors.
- Infrared thermometer
  Distance: one inch to infinity
  Range: ±60°C from ambient
  Field of view: 6°
  Spectral response: 8-14 um
  Accuracy: ±0.5°C
  Repeatability: ±0.1°C
  Emissivity: 0.99
  Operating distance: 1 inch to infinity
- Ambient temperature
  Range: 0°C to 60°C
  Accuracy: ±0.5°C
  Resolution: 0.1°C
- Humidity
  Range: 0 to 100%
  Accuracy: ±5%
- Solar Radiation:
  Range: 0 to 100 mW/cM^2
  Accuracy: ±10%
- Response Time:
  Screen update <2.0 seconds
  Sample frequency <0.5 seconds
- Microprocessor: 64-K — 8 bit.
- Display: 2½ × 1½ LCD on processor
  1½ × 1 inch on sensor gun
- Serial Interface:
  RS-232 25 pin male connection
  Band Rates: 50-2400 (selectable)
  Character sizes: 5-8 (selectable)
  other download parameters also selectable
- Softside carry case
- Warranty: 1 year
- Power — 6 C cell batteries, with an expected life of 20 operating hours
- Recharging port provided for use with rechargeable batteries

base for his crop. By examining seasonal graphs of the normal index readings for his crop as a function of crop growth stage, a user can determine if the index readings he is obtaining are within or outside the range of normally expected values. This approach allows for the tailoring of crop stress management to suit specific agronomic objectives such as increasing sugar in grapes.

Technique 4 — Cumulative Index Values: Another approach is to take *Scheduler* readings on a systematic basis, such as daily, every second day, etc. When data is collected in this manner, it is possible to begin summing the stress index readings. This approach is similar to the growing degree-day approach, except that plant stress readings are substituted for air temperature readings.

TABLE 3. Selected Institutions Where Scheduler Research Was Conducted in 1986 and The Results Obtained.

Institution	Crop	Data Obtained Showing the Scheduler Indices are Related to:
Texas A&M	Turf	Water use, plant health
Univ. of Nebraska	Corn, Wheat Soybeans	Baseline confirmation
Oregon State Univ.	Potatoes	Water use, soil water, yield quality
Fresno State Univ.	Grapes	Water use, stomatal resistance, yield quality, disease
USDA, Arizona	Alfalfa	Water use, yields
Univ. of Calif.	Cotton	Leaf water potential, yields

In addition, we obtained data from independent researchers and the USDA on the following crops: pecans, jojoba, nectarines, almonds, tomatoes, cucumbers, celery, wheat, sugar beets, and several others. Extensive research is also being conducted in 1988 on several crops.

Studies have shown that cumulative values are strongly related to the total amount of water used. This makes it possible to schedule irrigations on crops where any stress must be avoided, but where over-irrigation must also be avoided, such as celery.

In addition to cumulative stress index values, it is also possible to cumulate VPD (vapor pressure deficit) values. Cumulative VPD values are a measure of how much drying power a crop has been exposed to, serving as an indicator of disease possibilities. VPD values for cumulative purposes can be collected whenever the user feels it is most appropriate. Currently, the calibration of all cumulative values is conducted by the user.

(Gardner is product technical manager, Standard Oil Engineered Materials Co., Solon, Ohio. His remarks were presented at October's Vineyard and Water Management Seminar at CSU/Fresno. The Scheduler costs approximately $4,300, with software available for another $400.)

TABLE 4. Applications for The Scheduler Plant Stress Monitor

The Scheduler provides data for a wide range of research applications.

- Scheduling irrigation in many crops.
- Scheduling STAM applications in rice.
- Controlling bunch-rot in grapes.
- Scheduling Round-up applications on weeds (the higher the stress, the lower the kill rate).
- Locating "hot spots" caused by disease, insects, compaction, plugged irrigation emitters, etc.
- Estimating daily evapotranspiration values.
- Measuring fruit temperatures in grapes and other crops.
- Measuring the temperature of vital plant parts, such as stem temperatures in grapes.
- Controlling humidity levels in vineyards.
- Generally reducing the amounts of over-irrigation.
- Quantifying the effect of chemical applications on plants. Herbicides, insecticides and fungicides affect plants to varying degrees.
- Quantifying the drying power of the air, to relate to disease factors.
- Estimating yield reductions due to stress.
- Controlling plant responses and fruit quality by careful management of stress levels.

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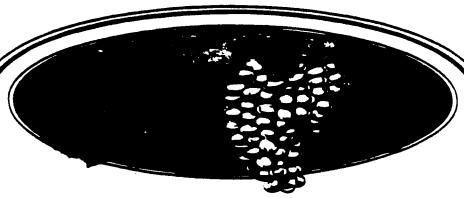

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HOW THE SCHEDULER MONITOR DETECTS CROP STRESS

Irrigation has traditionally been scheduled according to factors that are lacking direct crop measurements. However, research scientists from Standard Oil Engineered Materials Co. determined that irrigation scheduling could be more efficient when the crop tells growers when to water. Leaders from the irrigation industry agreed and encouraged these R & D scientists to pursue this effort.

Starting with this concept, the scientists developed the *Scheduler*™ plant stress monitor, a sophisticated but easy-to-use tool that allows maximum efficiency in scheduling irrigation.

The *Scheduler* is the first portable unit of its kind for determining crop stress. A computer calculates plant stress from inputs provided by an infrared thermometer and sensors for air temperature, relative humidity and sunlight intensity. Plant stress is detected 3-5 days before crop yield is adversely affected.

"The accuracy of the *Scheduler* has been proven by years of field testing and use at more than 30 sites across the nation," said Standard's Dr. Bronson Gardner, one of the product's developers and scientist in charge of field trials.

"The *Scheduler* detects a plant that is not transpiring at an optimum rate, this plant is under stress," Gardner explained. "A majority of the time, it is simply stress due to the lack of water, which indicates the need for irrigation, but there are times when the plant will undergo stress due to over-irrigation, disease, insect damage and nutritional deficiencies.

Wines & Vines Photo

Prof. Charles Krauter demonstrated the Scheduler.

"If there is sufficient available soil moisture, and the plant continues being stressed after an initial reaction to being watered, then you know there is another problem. In this instance the *Scheduler* is being used as a diagnostic tool," he said.

As carbon-dioxide enters a leaf and water evaporates from the leaf, the plant is transpiring. The small pores on the surface of leaves (stomata) regulate this transpiration by opening and closing. The stomates constrict or completely close when the plant is under stress and this slows or stops transpiration.

As transpiration slows, the leaf temperature rises (relative to the surrounding environment). The *Scheduler* plant stress monitor measures those minute changes in leaf temperature and interprets them as the stress index.

Although the *Scheduler* is an extremely compact unit powered by a rechargeable battery, the unit contains a powerful yet simple computer program to calculate the crop stress, provide a readout and store information. A graphic readout shows the pattern of plant stress as it develops. Data for up to 30 individual fields during a 15-day period can be retained in the unit's memory. By linking to an external computer/printer, a permanent record can be retained or a data base established.

The device is programmable for numerous crops. Stress indexes are developed for each crop because different plant species relate to the environment differently. "For each crop we have to know the "base-line" or normal reading for a non-stressed crop," Gardner explained. "Departures from that base-line indicate some type of stress. Once the plant stress has increased to a predetermined level, irrigation needs to begin.

"Depending upon the crop," he added, "growers may want to provide a certain amount of stress at specific growth phases, or provide extra irrigation at points critical to crop yield. The bottom line is that the *Scheduler* gives growers flexibility in managing their crops never before available."

Fig. 1. Side View

$T_1 = \frac{1}{2}$ of the angular field of view

1) $\chi = \sqrt{D^2 + H^2}$

2) $G = \sin^{-1}\left(\frac{D}{\chi}\right) - T_1$

3) $C = 90 - T_1 - G$

4) $S = \frac{\sin(T_1) \cdot \chi}{\sin(G + 90)}$

5) $K = 90 - G - 2 \cdot T_1$

Note: IF K < .001, Set K = 1° .001 .001

6) $L = \frac{\sin(T_1) \cdot \chi}{\sin(K)}$

7) $L + S$ = Total Length of Field of View

$L + S = 32.65 + 37.55 = 70.2$ cm

example: Instrument field of view = 4°, $T_1 = 2$

$D = 400$ cm $H = 200$ cm

$\chi = \sqrt{400^2 + 200^2} = 447.2$ cm

$G = \sin^{-1}\left(\frac{400}{447.2}\right) - 2.0 = 61.44°$

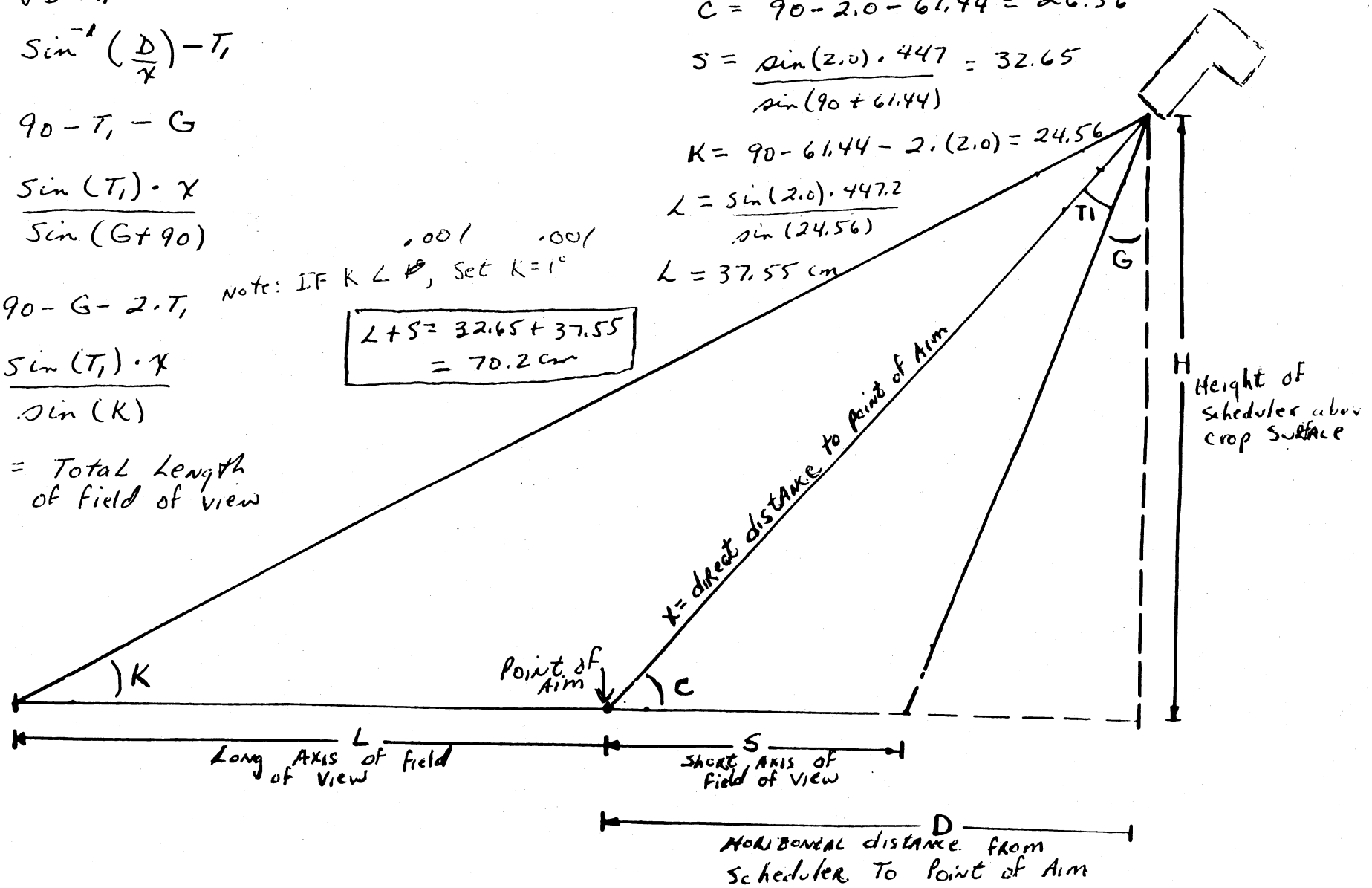
$C = 90 - 2.0 - 61.44 = 26.56°$

$S = \frac{\sin(2.0) \cdot 447}{\sin(90 + 61.44)} = 32.65$

$K = 90 - 61.44 - 2.(2.0) = 24.56$

$L = \frac{\sin(2.0) \cdot 447.2}{\sin(24.56)}$

$L = 37.55$ cm



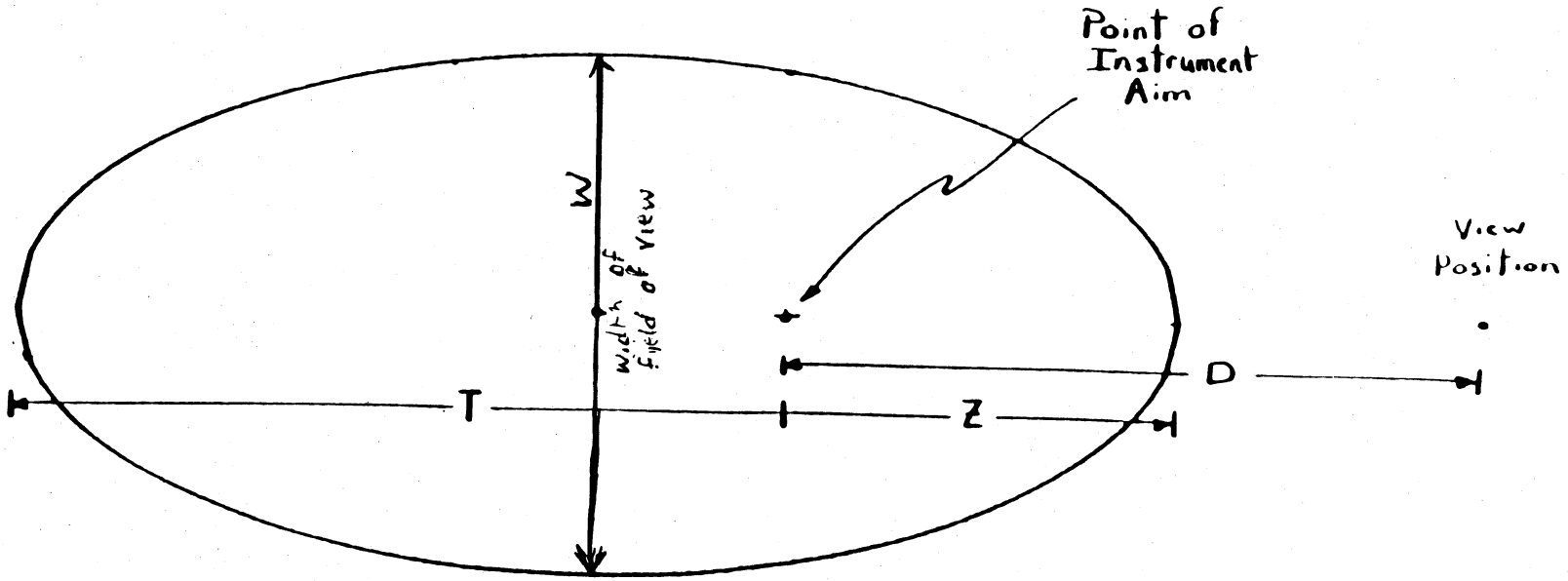
1986

Fig. 2. Top View

8) $W \cong 2 \cdot X \cdot TAN(T_1)$

(example) $W \cong 2 \cdot 447.2 \cdot Tan(2°)$

$W \cong 31.2$ cm



Source:
David Nielsen
USDA
AKron, Colorado

```
REM PROGRAM TO CALCULTE THE SPOT SIZE OF AN INFRARED THERMOMETER
CLS
PI = 3.1416
PRINT "INSTRUMENT FIELD OF VIEW IN DEGREES        ";
INPUT T1
T1 = T1 * (PI / 180)
T1 = T1 / 2

PRINT "INSTRUMENT HEIGHT ABOVE CANOPY (ANY UNITS) "
INPUT H

PRINT "HORIZONTAL DISTANCE TO VIEWED SURFACE      "
PRINT "(use same units as instrument height)      "
INPUT D

REM THE UNITS OF H AND D MUST BE THE SAME
REM ALL TRIGONOMETRIC FUNCTIONS ARE CALCULATED IN RADIANS
X = SQR(D ^ 2 + H ^ 2)
IF H = 0 AND D = 0 THEN D = 1
C = ATN(H / D)
G = PI / 2 - T1 - C
S = SIN(T1) * X / (SIN(G + PI / 2))
K = (PI / 2) - G - 2 * T1
D = SIN(K)
IF SIN(K) < .02 THEN D = .02
L = SIN(T1) * X / D
T = L + S
W = 2 * X * TAN(T1)
A = PI * T * W / 4

REM CONVERT ANGLES FROM RADIANS TO DEGREES
G = G * 57.295
C = C * 57.295
K = K * 57.295

PRINT "AREA                  ="; : PRINT A; :  PRINT "UNITS SQUARED      "
PRINT "TOTAL LENGTH OF SPOT =="; : PRINT T; :  PRINT "UNITS               "
PRINT "MAXIMUM SPOT WIDTH   =="; : PRINT W; :  PRINT "UNITS               "
PRINT "SHORT LENGTH OF SPOT =="; : PRINT S; :  PRINT "UNITS               "
PRINT "LONG LENGTH OF SPOT  =="; : PRINT L; :  PRINT "UNITS               "

REM check to see if sky is probably viewed by the irt

IF K < 1 THEN PRINT "SOME SKY SEEN"
IF K < -1 THEN PRINT "DO NOT USE AT THIS ANGLE"


PRINT "          GENERAL SHAPE OF AN IRT FIELD OF VIEW      ";
PRINT "                                  *      *      *    *";
PRINT "                               *           |              *     ";
PRINT "  observer aims at x   * short axis        |       long axis";
PRINT "     o                  -----------x-------------------------*";
PRINT "                         *                 |                  * ";
PRINT "                              *            |                *";
PRINT "                                   *      *      *    * ";
PRINT "                                     maximum width    ";
```

PROGRAM AND PROCECDURES DEVELOPED BY
DAVID NIELSEN AND KENITH HUBBARD

```
100 ! *THIS PROGRAM CALCULATES*
110 ! *THE AREA OF THE VIEWED *
120 ! *SPOT SEEN BY AN IRT    *
130 ! *GIVEN HT. OF THE IN-   *
140 ! *STRUMENT ABOVE THE     *
150 ! *VIEWED SURFACE, HORIZ- *
160 ! *ONTAL DISTANCE FROM THE*
170 ! *INSTRUMENT LOCATION TO *
180 ! *THE VIEWED SURFACE AND *
190 ! *THE FIELD OF VIEW OF   *
200 ! *THE INSTRUMENT         *
201 ! *a IS 1/2 OF THE MINOR  *
    202 ! * AXIS
      *
203 ! *b IS 1/2 OF THE MAJOR  *
    204 ! * AXIS
      * 205 ! ****************
    *******
210 ! **************************
220 DEG
230 CLEAR
240 DISP "ENTER INSTRUMENT HEIGH
    T ABOVE   VIEWED SURFACE" @
    INPUT H
250 DISP "ENTER HORIZONTAL DISTA
    NCE FROM  INSTRUMENT LOCATIO
    N TO VIEWED   SURFACE" @ INP
    UT D
260 DISP "ENTER INSTRUMENT FIELD
     OF VIEW" @ INPUT T1
270 T1=T1/2
280 C=ATN(H/D)
290 X=SQR(D^2+H^2)
300 G=90-T1-C
310 K=C-T1
320 Z=SIN(T1)*X/SIN(G+90)
330 T=SIN(T1)*X/SIN(K)
340 B=.5*(Z+T)
341 M=X*TAN(T1)
342 X1=-D
343 H1=-(D+T-B)
344 A2=M^2/(1-(-D-H1)^2/B^2)
350 A=SQR(A2)
360 A1=3.14159*A*B
370 DISP
380 DISP USING 390 ; "a =",A
390 IMAGE 3A,DDD.DD
400 DISP USING 390 ; "b =",B
410 DISP USING 420 ; "AREA =",A1
420 IMAGE 6A,DDD.DD
430 END
```

Method For Calculating Spot Size of Instrument

Given: H = Instrument height above viewed surface

D = Horizontal Distance from instrument to viewed surface

TI = Instrument field of view

See Figure 1

Let TI now become half of the field of view

Calculate the angle C from D & H

Calculate the length X from D & H

Calculate the angle G from TI and C

Calculate the angle K from TI and C

(diagonal line intersecting parallel lines, alternate interior angles)

Calculate Length Z from TI, G and X in Law of Sines

Calculate Length T from TI, K and X in Law of Sines

Calculate Length B as $\frac{1}{2}$ of (Z+T); B is length of $\frac{1}{2}$ major axis

Now See Fig. 2

Calculate M from TI and X;

Solve equation for ellipse for A knowing specific point (X1, Y) = (-D, M)

and center of ellipse at (H1, K1) = (-(D+T-B), 0)

Calculate area of ellipse as $\pi * A * B$

Example: Given Instrument height above surface = H = 200 cm

Horizontal distance from instrument to viewed sfc D = 400 cm

Instrument field of view = TI = 5°

Half of field of view = TI = 2.5°

angle C = $TAN^{-1}\left(\frac{200}{400}\right)$ = 26.57°

Length X = $\sqrt{(400)^2+(200)^2}$ = 447.2 cm

angle G = 90° − 2.5° − 26.57° = 60.93°

angle K = 26.57° − 2.5° = 24.07°

Length Z = (sin(2.5°) * 447.2) / sin(60.93° + 90°) = 40.15 cm

Length T = (sin(2.5°) * 447.2) / sin(24.07°) = 47.83 cm

Length B = $\frac{1}{2}$ (40.15 + 47.83) = 43.99 cm

Length M = 447.2 * TAN(2.5) = 19.53 cm

Center of ellipse has coordinates (−(400 + 47.83 − 43.99), 0) = (−403.84, 0)

Coordinates of known point on ellipse = (−400, 19.53)

$$\text{Length } A = \sqrt{\frac{(19.53)^2}{1 - \frac{(-400 - (-403.84))^2}{(43.99)^2}}} = 19.60$$

Area of ellipse = π (19.60)(43.99) = 2708.69 cm^2

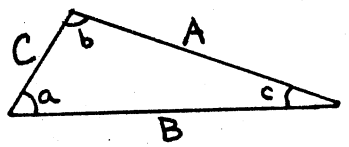
Fig. 1. Side View

TI = $\frac{1}{2}$ of the angular field of view

To calculate lengths Z and T
use Law of Sines

$$\frac{\sin(TI)}{Z} = \frac{\sin(90+G)}{X} \quad \text{and} \quad \frac{\sin(TI)}{T} = \frac{\sin(K)}{X}$$

Law of Sines



$$\frac{\sin a}{A} = \frac{\sin b}{B} = \frac{\sin c}{C}$$

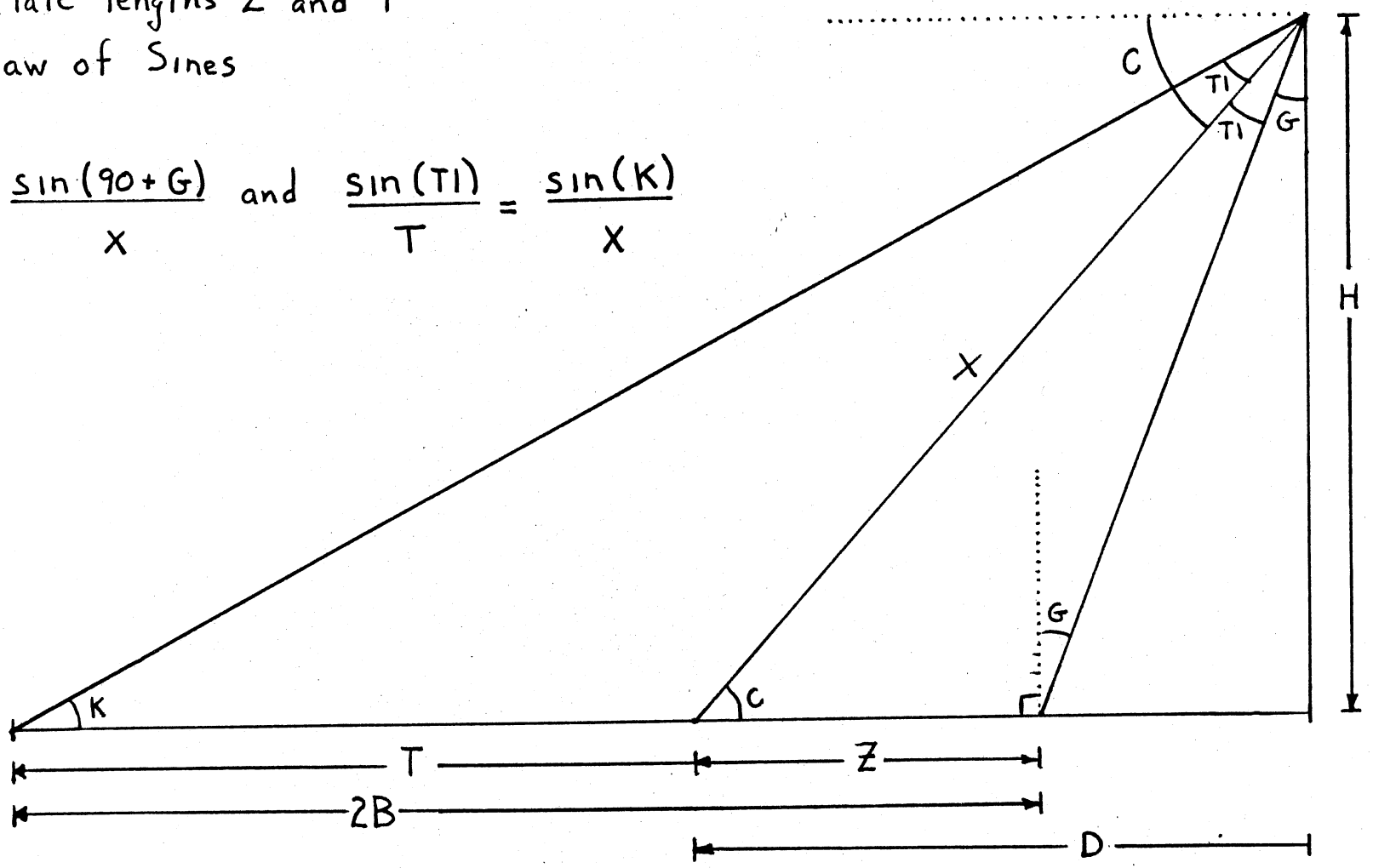
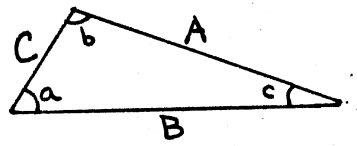


Fig. 1. Side View

TI = $\frac{1}{2}$ of the angular field of view

Law of Sines



$$\frac{\sin a}{A} = \frac{\sin b}{B} = \frac{\sin c}{C}$$

To calculate lengths Z and T
use Law of Sines

$$\frac{\sin(TI)}{Z} = \frac{\sin(90+G)}{X} \quad \text{and} \quad \frac{\sin(TI)}{T} = \frac{\sin(K)}{X}$$

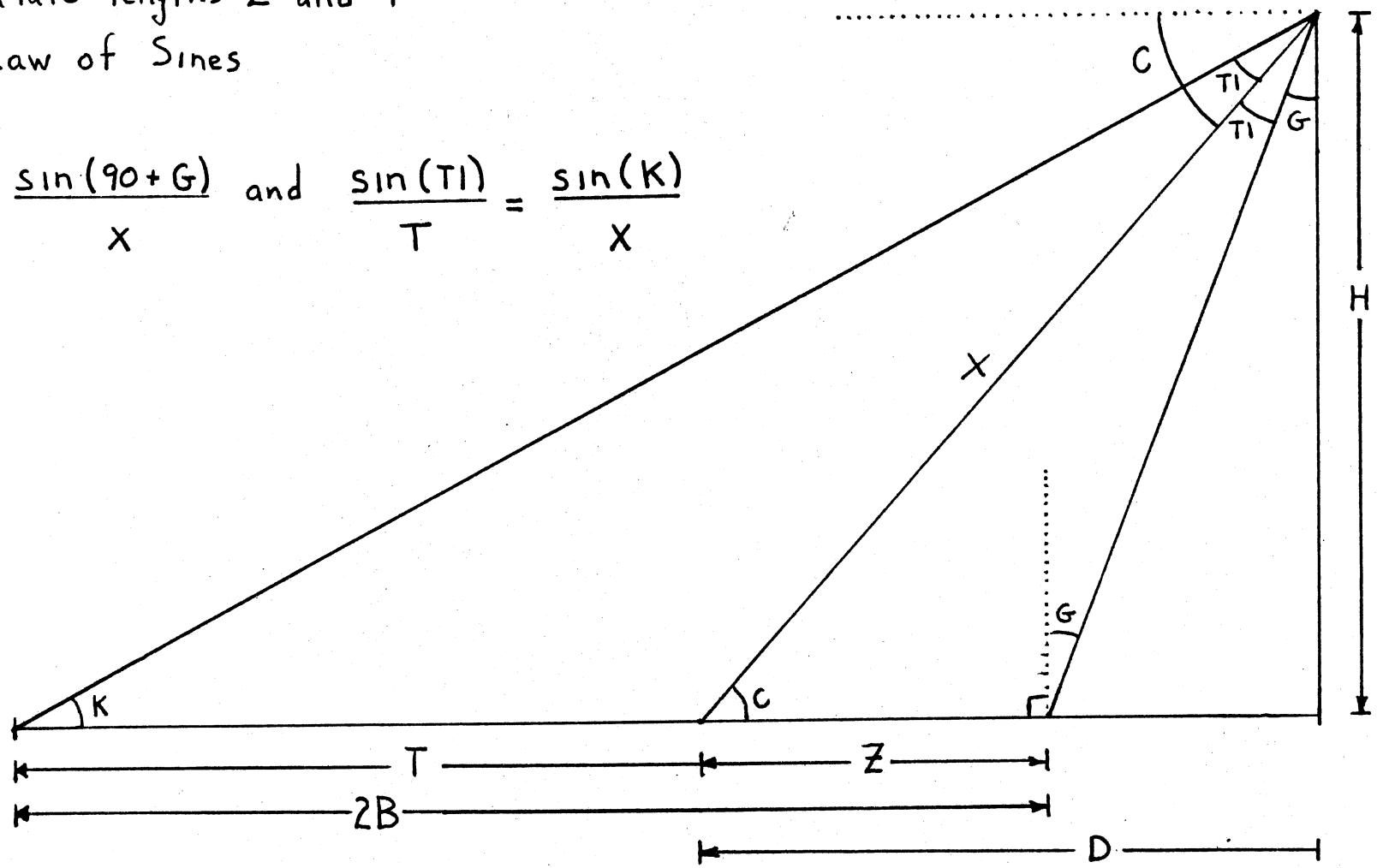


Fig. 2

$(H1, K1)$ = center of ellipse

$= (-(D+T-B), 0)$

Equation of Ellipse

$$\frac{X1 - H1}{B^2} + \frac{Y - K1}{A^2} = 1$$

Solve this equation for A from knowledge of location of a given point on Ellipse $(-D, M)$

so, substituting for $X1, H1, Y, K1$

$$\frac{(-D - (-(D+T-B)))^2}{B^2} + \frac{(M - K1)^2}{A^2} = 1$$

$$\frac{(M-K1)^2}{A^2} = 1 - \frac{(-D - (-(D+T-B)))^2}{B^2}$$

$$A^2 = \frac{(M-K1)^2}{1 - \frac{(-D - (-(D+T-B)))^2}{B^2}}$$

$(K1 = 0)$

$$A = \sqrt{\frac{m^2}{1 - \frac{(-D - (-(D+T-B)))^2}{B^2}}}$$

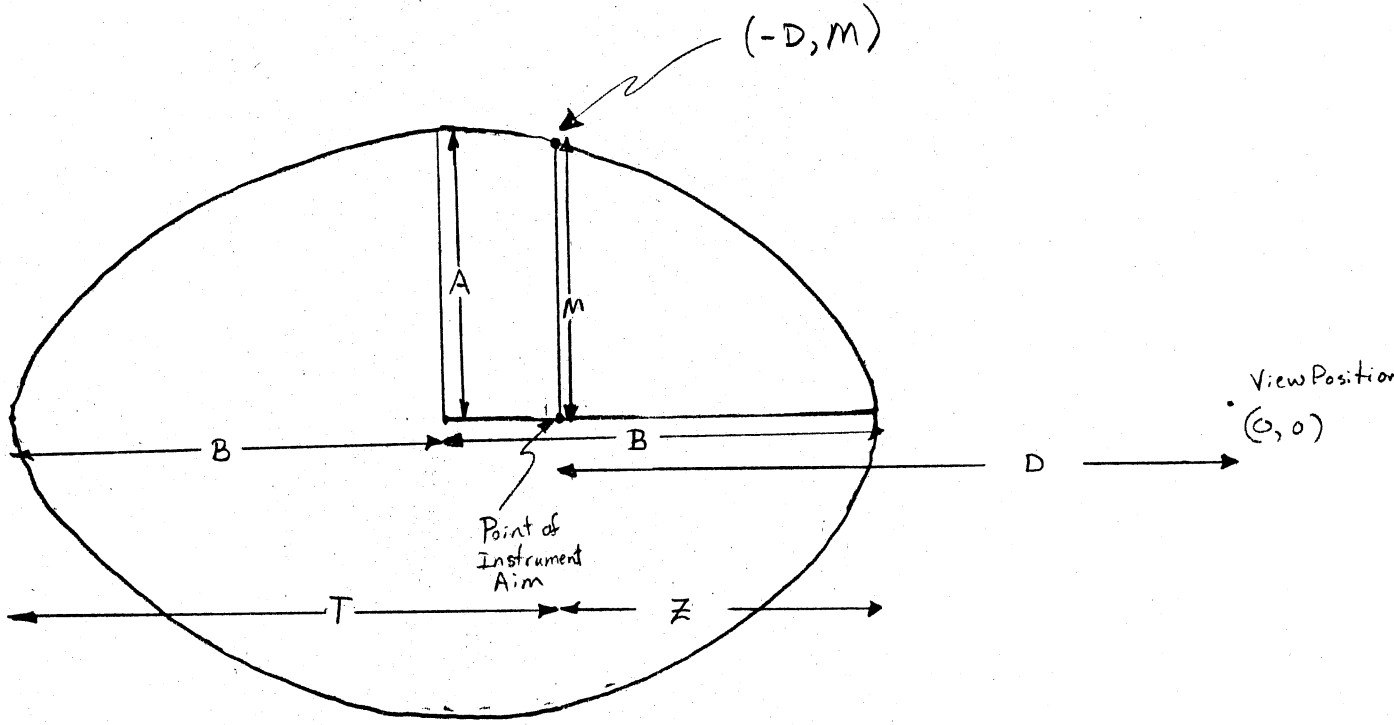
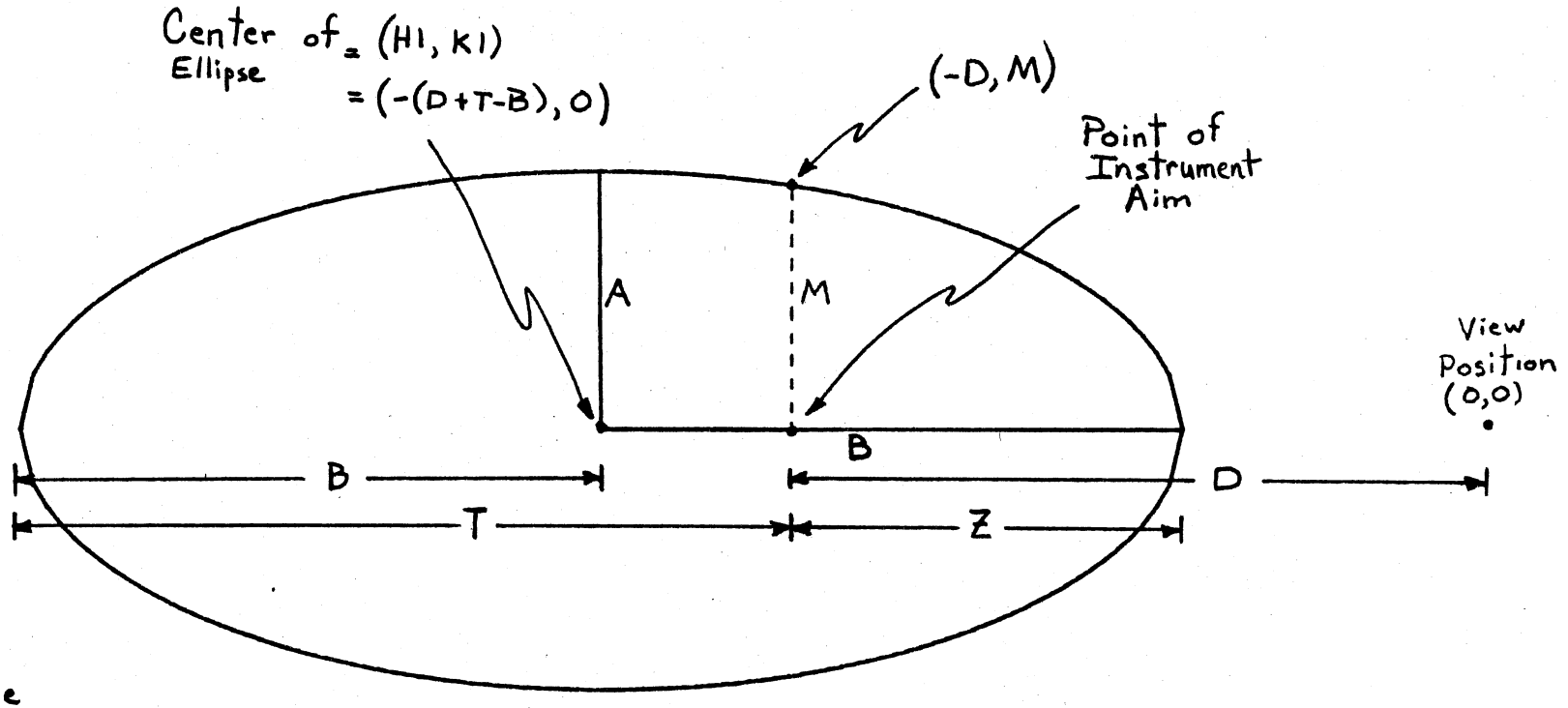


FIG. 2. TOP VIEW



Equation of Ellipse

$$\frac{(X1-H1)^2}{B^2} + \frac{(Y-K1)^2}{A^2} = 1$$

Solve this equation for A from knowledge of location of a given point on ellipse, (-D, M)

Substituting for X1, H1, Y, K1:

$$\frac{(-D-(-(D+T-B)))^2}{B^2} + \frac{(M-K1)^2}{A^2} = 1$$

$$\frac{(M-K1)^2}{A^2} = 1 - \frac{(-D-(-(D+T-B)))^2}{B^2}$$

$$A = \sqrt{\frac{M^2}{1 - \frac{(-D-(-(D+T-B)))^2}{B^2}}}$$

Fig. 1. Side View

$T_1 = \frac{1}{2}$ of the angular field of view

1) $\chi = \sqrt{D^2 + H^2}$

2) $G = \sin^{-1}\left(\frac{D}{\chi}\right) - T_1$

3) $C = 90 - T_1 - G$

4) $S = \frac{\sin(T_1) \cdot \chi}{\sin(G + 90)}$

5) $K = 90 - G - 2 \cdot T_1$ Note: IF $K < 1°$, Set $K = 1°$

6) $L = \frac{\sin(T_1) \cdot \chi}{\sin(K)}$

7) $L + S$ = Total Length of Field of View

Example: Instrument Field of View = 4°, $T_1 = 2°$

$D = 400$ cm $H = 200$ cm

$\chi = \sqrt{400^2 + 200^2} = 447.2$ cm

$G = \sin^{-1}\left(\frac{400}{447.2}\right) - 2.0 = 61.44°$

$C = 90 - 2.0 - 61.44 = 26.56°$

$S = \frac{\sin(2.0) \cdot 447}{\sin(90 + 61.44)} = 32.65$

$K = 90 - 61.44 - 2 \cdot (2.0) = 24.56$

$L = \frac{\sin(2.0) \cdot 447.2}{\sin(24.56)}$

$L = 37.55$ cm

$L + S = 32.65 + 37.55 = 70.2$ cm

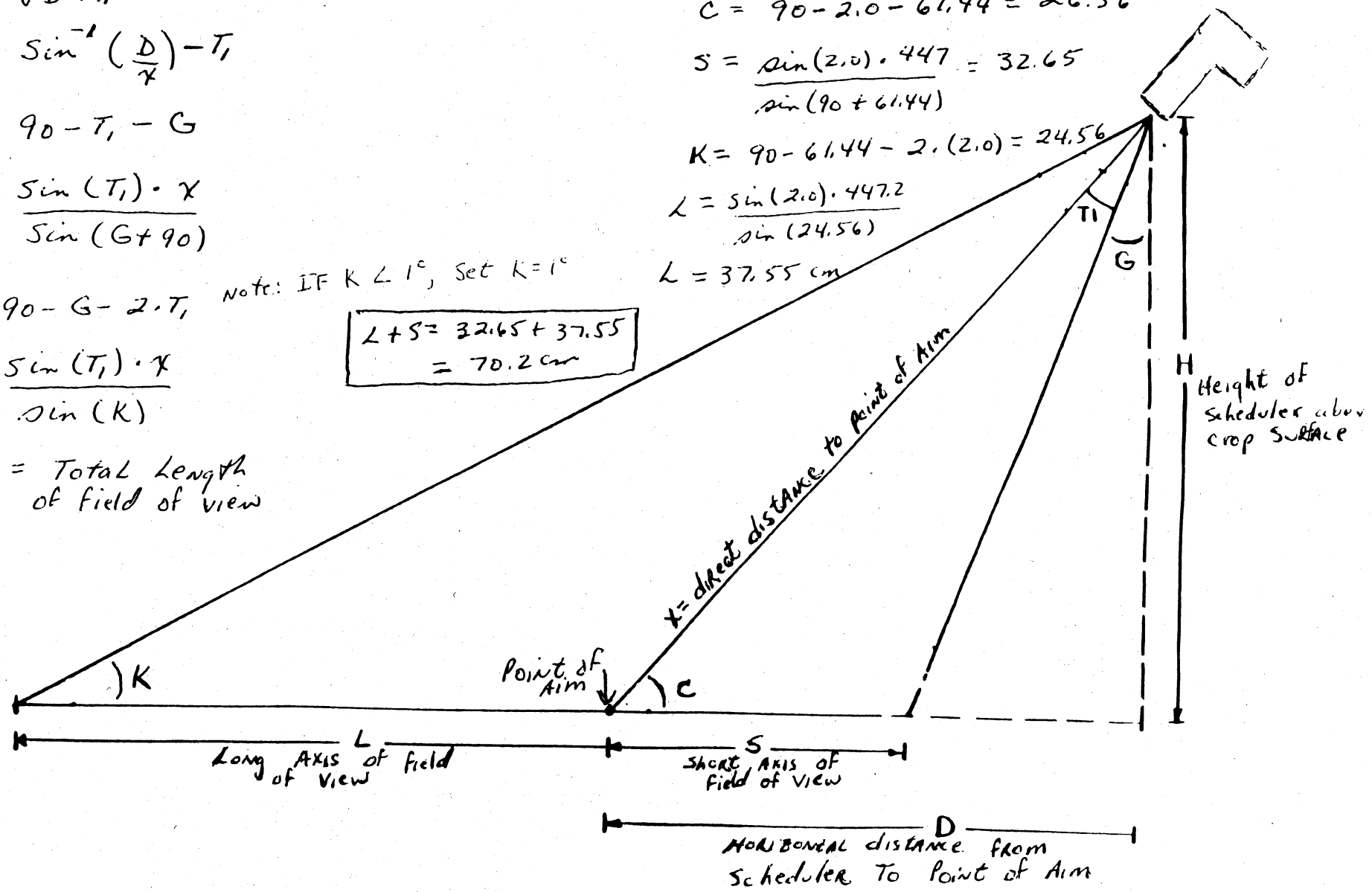
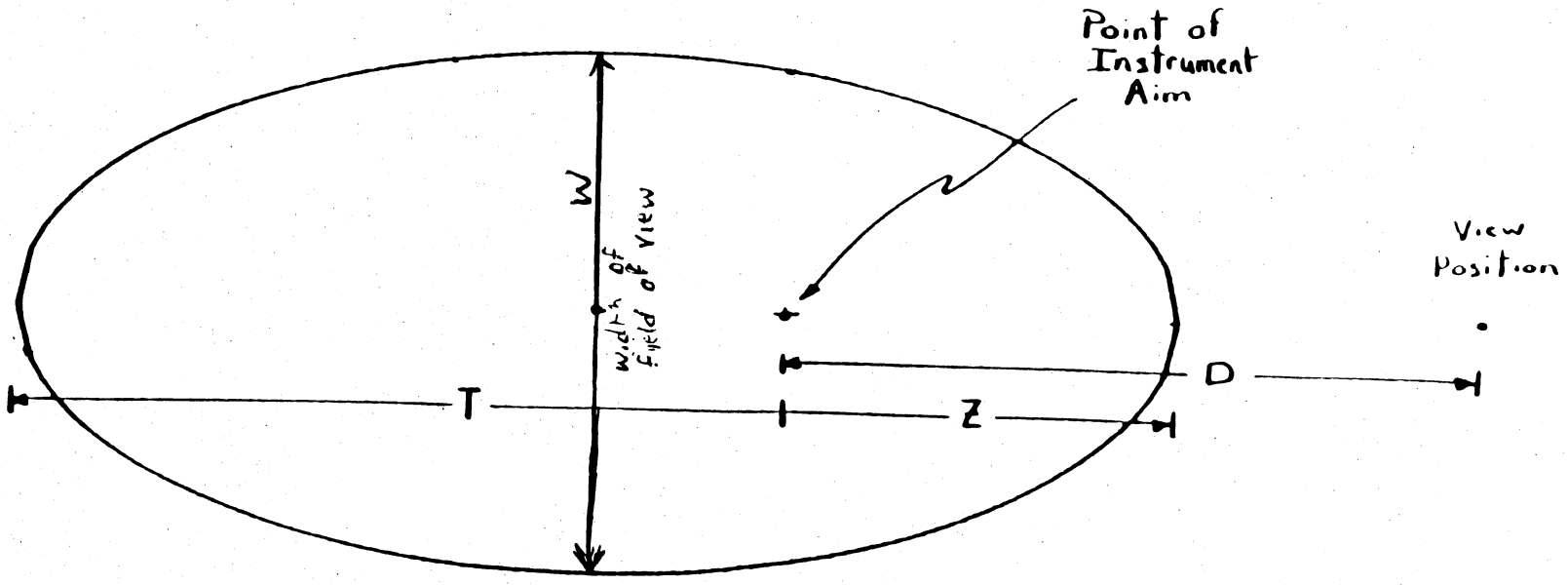


Fig. 2. Top View

8) $W \cong 2 \cdot X \cdot TAN(T_1)$

(example) $W \cong 2 \cdot 447.2 \cdot Tan(2°)$

$W \cong 31.2$ cm



Source:
David Nielsen
USDA
AKron, Colorado

APPENDIX I

Calculating the spot size of an IRT

F_2 = (FOV/2) The IRT in the Scheduler™ has an 8^o FOV at the extremes, about 6^o FOV at the half power points.

H = Height of IRT above the crop canopy

D = Horizontal distance from the IRT to the target.

S = Short axis of the spot size. The distance from the target back toward the observer to the edge of the FOV.

L = Long axis of the spot size. The distance from the target away from the observer to the edge of the FOV.

K = Indicator of whether or not sky is seen. If K is positive, no sky is seen. If K is negative, sky is seen. If K is between -1 and 0, the error is probably small. For calculation purposes, if K is less than 0.001, set K=0.001, or the trigonometric functions used will blow up. If K is less than -1, the IRT readings will be seriously biased by sky temperature.

W = Maximum width of the spot size

Calculations

All trig functions are in degrees. The example given is for a FOV of 6^{o}, height of 4 ft. and target distance of 25 ft.

*F_2 = FOV/2

1) $Z = (D^2 + H^2)^{1/2} = (16 + 625)^{1/2} = 25.3$

2) $G = \text{Sin}^{-1}\left(\frac{D}{Z}\right) - F_2 = \text{Sin}^{-1}\left(\frac{25}{25.318}\right) - 3 = 77.9$

3) $C = 90 - F_2 - G = 9.09$

4) $S = \frac{Z \sin(F_2)}{\sin(G + 90)} = 6.3$ ft.

5) $K = 90 - G - 2F_2$, If $K < 0.001$, then $K = 0.001$
If $K < 0$, Then "sky is seen"
If $K < -1$, Then "Do not use at this angle"
For this example, $K = 6.1$

6) $L = \frac{Z \text{ Sin } (F_2)}{\text{Sin } (K)} = 12.5$ ft.

7) T = TOTAL length of spot size = L + S
= 18.8

8) $W = 2 Z \tan(F_2) = 2.6$ ft.

9) Total area viewed = 3.14159 TW/4
= 39.2 $ft.^2$

Fig. 1. Side View

$T1 = \frac{1}{2}$ of the angular field of view

1) $X = \sqrt{D^2 + h^2}$

2) $G = \sin^{-1}\left(\frac{D}{X}\right) - T_1$

3) $C = 90 - T_1 - G$

4) $S = \frac{\sin(T_1) \cdot X}{\sin(G+90)}$

5) $K = 90 - G - 2 \cdot T_1$ IF $K < 1°$ then set $K = 1°$

6) $L = \frac{\sin(T_1) \cdot X}{\sin(K)}$

7) $W = 2 \cdot X \cdot \tan(T_1)$

8) $L+S$ = TOTAL Length of field of view

example: Instrument field of view = 5° $T_1 = 2.5°$

D = 400 cm

H = 200 cm

$X = \sqrt{400^2 + 200^2} = 447.2$ cm

$G = \sin^{-1}\left(\frac{400}{447.2}\right) - 2.5 = 60.94°$

$C = 90 - 2.5 - 60.94 = 26.56°$

$S = \frac{\sin(2.5) \cdot 447}{\sin(90+60.94)} = 40.14$ cm

$K = 90 - 60.94 - 2 \cdot (2.5) = 24.06°$

$L = \frac{\sin(2.5) \cdot 447.2}{\sin(24.06)} = 47.84$ cm

$W = 39.05$ cm

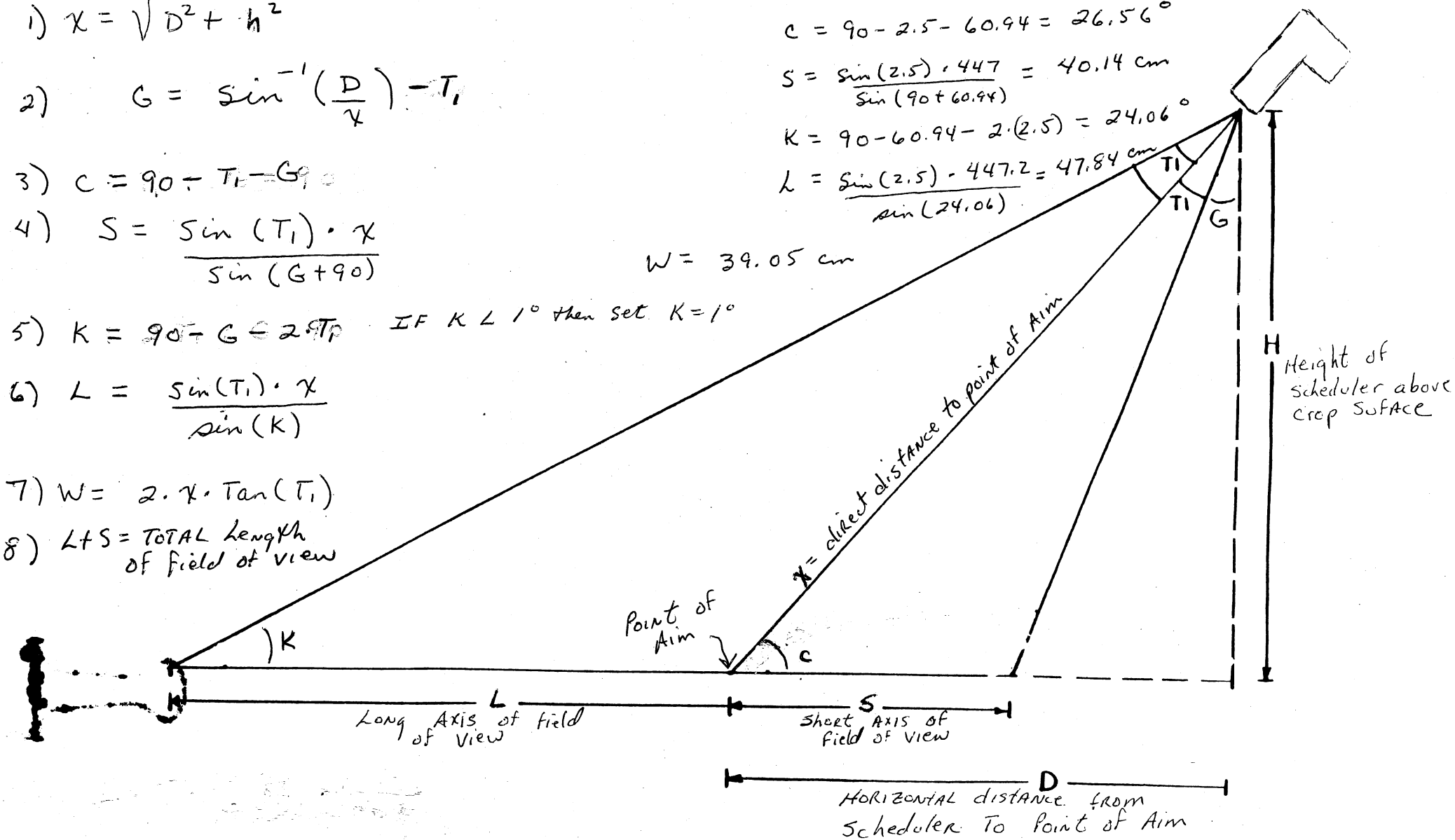


Fig. 2. Top View

8) $W = 2 \cdot X \cdot \text{TAN}(T_1)$

(example) $W = 2 \cdot 447.2 \cdot \text{Tan}(2°)$

$W = 31.2$ cm

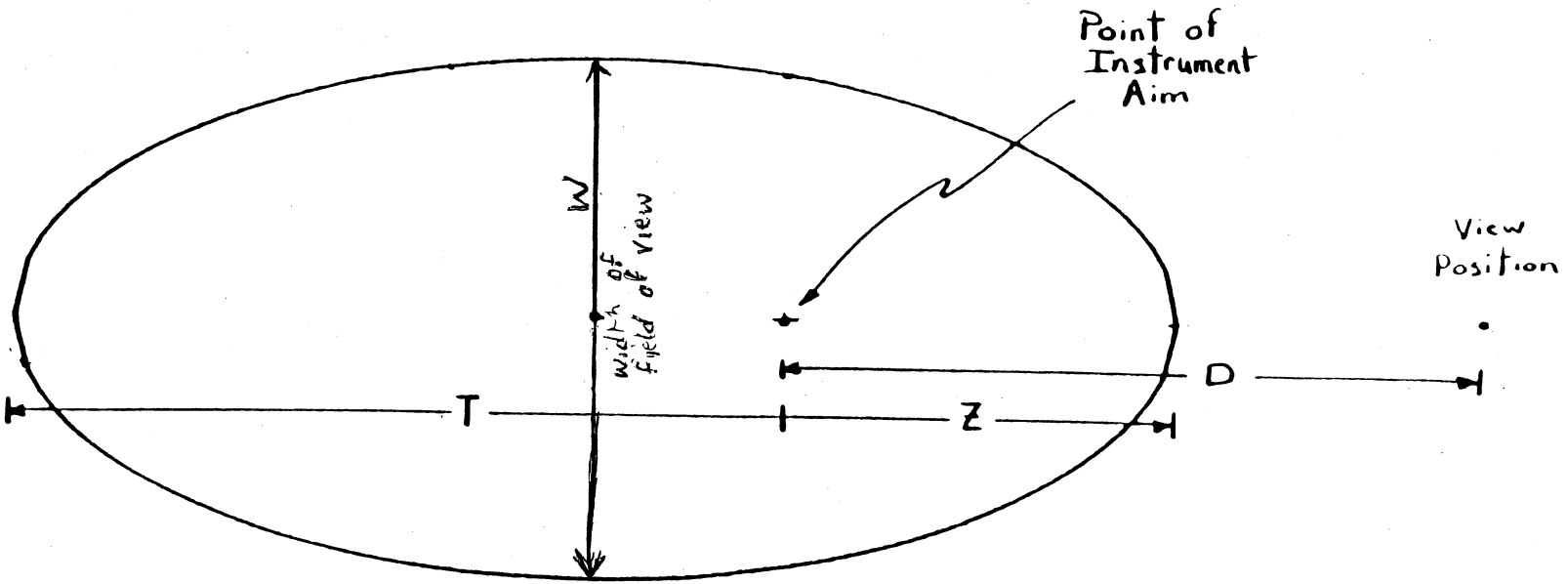
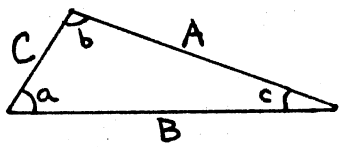


Fig. 1. Side View

TI = $\frac{1}{2}$ of the angular field of view

Law of Sines



$$\frac{\sin a}{A} = \frac{\sin b}{B} = \frac{\sin c}{C}$$

To calculate lengths Z and T
use Law of Sines

$$\frac{\sin(TI)}{Z} = \frac{\sin(90+G)}{X} \quad \text{and} \quad \frac{\sin(TI)}{T} = \frac{\sin(K)}{X}$$

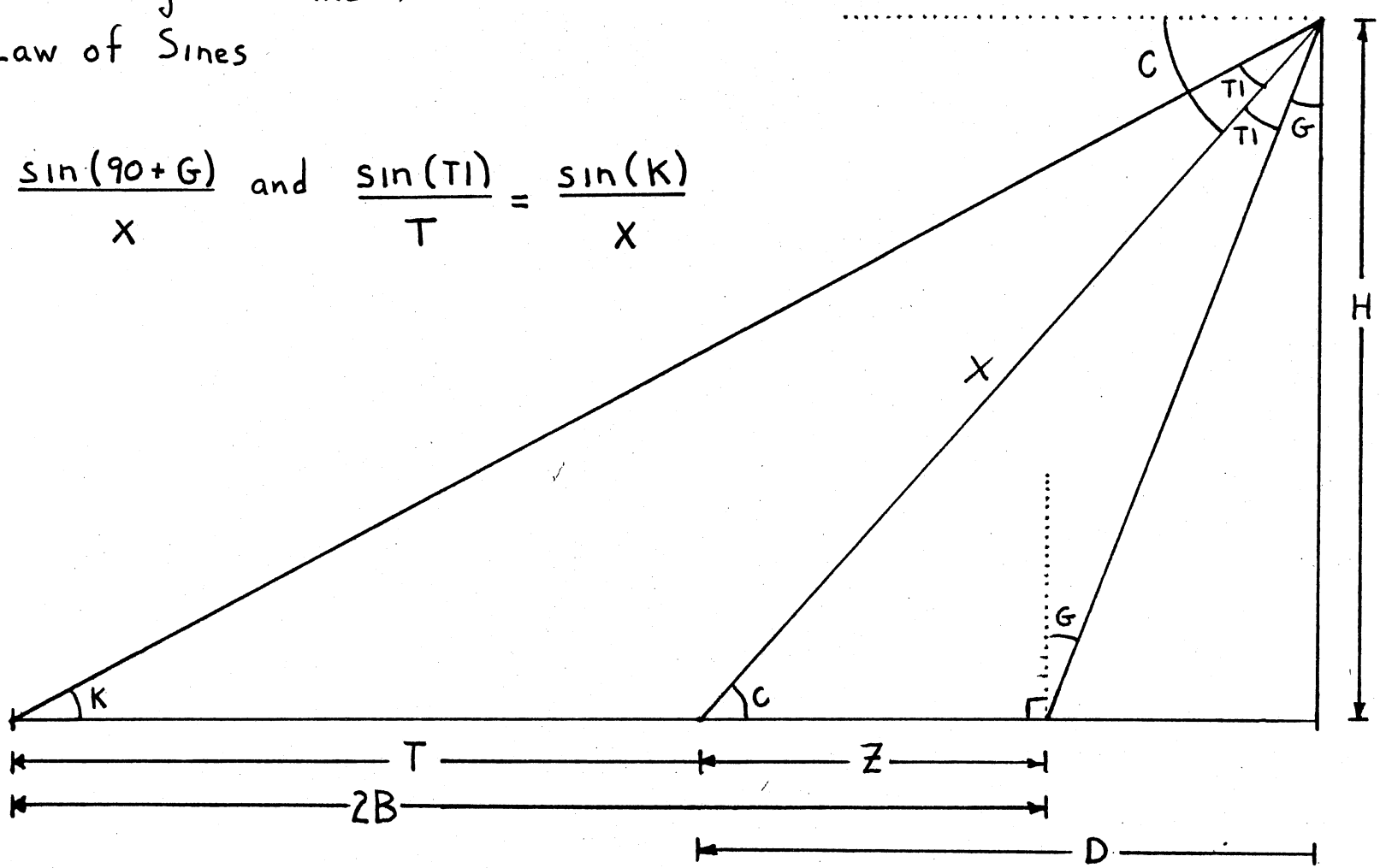
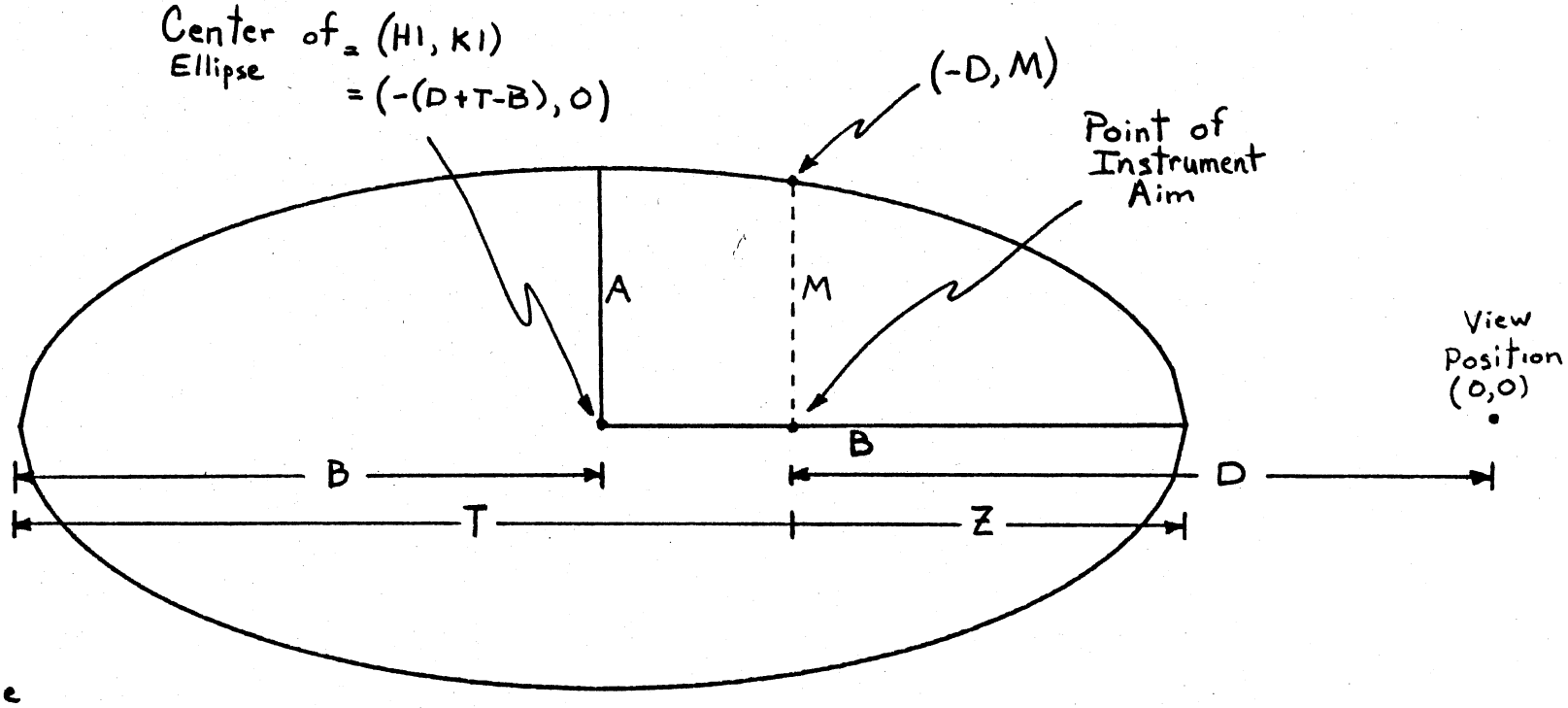


FIG. 2. TOP VIEW



Equation of Ellipse

$$\frac{(X1-H1)^2}{B^2} + \frac{(Y-K1)^2}{A^2} = 1$$

Solve this equation for A from knowledge of location of a given point on ellipse, (-D, M)

Substituting for X1, H1, Y, K1:

$$\frac{(-D-(-(D+T-B)))^2}{B^2} + \frac{(M-K1)^2}{A^2} = 1$$

$$\frac{(M-K1)^2}{A^2} = 1 - \frac{(-D-(-(D+T-B)))^2}{B^2}$$

$$A = \sqrt{\frac{M^2}{1 - \frac{(-D-(-(D+T-B)))^2}{B^2}}}$$

Example: Given Instrument height above surface = H = 200 cm

Horizontal distance from instrument to viewed sfc D = 400 cm

Instrument field of view = TI = 5°

Half of field of view = TI = 2.5°

angle C = $TAN^{-1}\left(\frac{200}{400}\right)$ = 26.57°

Length X = $\sqrt{(400)^2+(200)^2}$ = 447.2 cm

angle G = 90° − 2.5° − 26.57° = 60.93°

angle K = 26.57° − 2.5° = 24.07°

Length Z = (Sin (2.5°) * 447.2) / Sin(60.93° + 90°) = 40.15 cm

Length T = (Sin (2.5°) * 447.2) / Sin(24.07°) = 47.83 cm

Length B = $\frac{1}{2}$ (40.15 + 47.83) = 43.99 cm

Length M = 447.2 * TAN (2.5) = 19.53 cm

Center of ellipse has coordinates (−(400 + 47.83 − 43.99), 0) = (−403.84, 0)

Coordinates of known point on ellipse = (−400, 19.53)

$$\text{Length A} = \sqrt{\frac{(19.53)^2}{1 - \frac{(-400 - (-403.84))^2}{(43.99)^2}}} = 19.60$$

Area of ellipse = π (19.60)(43.99) = 2708.69 cm^2

1) $x = \sqrt{D^2 + k^2}$

$D = 400$

$x = 447.2$

$G = 60.93$

2) $T_1 + G = \sin\left(\frac{D}{x}\right)^{-1}$

3) $C. + T_1 + G = 90$

4) $S = \frac{\sin(T_1) \cdot x}{\sin(G + 90)}$

5) $K + 2 \cdot T1 + G = 90$

$K = 90 - G - 2 \cdot T_1$

6) $L = \frac{\sin(T_1) * x}{\sin(K)}$

7) $W = 2 \cdot \tan(T_1) \cdot D$

$= 2 \cdot x \cdot \tan(T_1)$

$= 2 \cdot x \cdot \tan(T_1)$

```
100 ! *THIS PROGRAM CALCULATES*
110 ! *THE AREA OF THE VIEWED *
120 ! *SPOT SEEN BY AN IRT     *
130 ! *GIVEN HT. OF THE IN-    *
140 ! *STRUMENT ABOVE THE      *
150 ! *VIEWED SURFACE, HORIZ- *
160 ! *ONTAL DISTANCE FROM THE*
170 ! *INSTRUMENT LOCATION TO *
180 ! *THE VIEWED SURFACE AND *
190 ! *THE FIELD OF VIEW OF   *
200 ! *THE INSTRUMENT         *
201 ! *a IS 1/2 OF THE MINOR  *
    202 ! * AXIS
      *
203 ! *b IS 1/2 OF THE MAJOR  *
    204 ! * AXIS
      * 205 ! ****************
    *******
210 ! ************************
220 DEG
230 CLEAR
240 DISP "ENTER INSTRUMENT HEIGH
    T ABOVE   VIEWED SURFACE" @
    INPUT H
250 DISP "ENTER HORIZONTAL DISTA
    NCE FROM  INSTRUMENT LOCATIO
    N TO VIEWED   SURFACE" @ INP
    UT D
260 DISP "ENTER INSTRUMENT FIELD
     OF VIEW" @ INPUT T1
270 T1=T1/2
280 C=ATN(H/D)
290 X=SQR(D^2+H^2)
300 G=90-T1-C
310 K=C-T1
320 Z=SIN(T1)*X/SIN(G+90)
330 T=SIN(T1)*X/SIN(K)
340 B=.5*(Z+T)
341 M=X*TAN(T1)
342 X1=-D
343 H1=-(D+T-B)
344 A2=M^2/(1-(-D-H1)^2/B^2)
350 A=SQR(A2)
360 A1=3.14159*A*B
370 DISP
380 DISP USING 390 ; "a =",A
390 IMAGE 3A,DDD.DD
400 DISP USING 390 ; "b =",B
410 DISP USING 420 ; "AREA =",A1
420 IMAGE 6A,DDD.DD
430 END
```

Method For Calculating Spot Size of Instrument

Given: H = Instrument height above viewed surface

D = Horizontal Distance from instrument to viewed surface

TI = Instrument field of view

See Figure 1

Let TI now become half of the field of view

Calculate the angle C from D & H

Calculate the length X from D & H

Calculate the angle G from TI and C

Calculate the angle K from TI and C

(diagonal line intersecting parallel lines, alternate interior angles)

Calculate Length Z from TI, G and X in Law of Sines

Calculate Length T from TI, K and X in Law of Sines

Calculate Length B as $\frac{1}{2}$ of (Z+T); B is length of $\frac{1}{2}$ major axis

Now See Fig. 2

Calculate M from TI and X;

Solve equation for ellipse for A knowing specific point (X1, Y) = (-D, M)

and center of ellipse at (H1, K1) = (-(D+T-B), 0)

Calculate area of ellipse as $\pi * A * B$

and soil-water dilution could have resulted in a reduction of osmotic potential, thus contributing to some of the observed reduction in growth. Further studies will be required to determine whether a reduction in root hairs or a change in osmotic potential could alter nutrient and water fluxes into wheat plants sufficiently to account for the observed differences in plant growth.

Root excision and defoliation studies indicate that compensatory development of an organ(s) tends to restore the original ratio (e.g., shoot to root), unless external or internal factors prevent it (Brouwer and deWit, 1969; Crossett et al., 1975). Although external factors known to affect coordinated growth can be controlled, the roots themselves can markedly influence the activities of the shoot (Torrey, 1976), thus affecting coordinated growth. Root-derived growth substances are known to affect shoot growth, including the outgrowth of lateral shoots (Skene, 1975). Although applications of exogenous growth regulators partially restored shoot growth of bean plants, growth restrictions of entire plants could not completely be overcome by any hormonal treatment tested (Carmi and Heuer, 1981). Our results with wheat demonstrate that limiting the space available for root growth and development can limit coordinated growth of the whole plant even when water and minerals are adequate. Whether this specific limitation of the root system in wheat restricts shoot growth through some hormonal system as proposed by Carmi and Heuer (1981) for bean plants remains to be elucidated.

ACKNOWLEDGMENTS

The authors gratefully acknowledge technical assistance from Mary Herrington Zuzel and chemical analyses performed by Paul Rasmussen and the Auburn University Soil Testing Laboratory.

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CANOPY TARGET DIMENSIONS FOR INFRARED THERMOMETRY[1]

J. C. O'Toole and J. Real[2]

Abstract

The increasing use of infrared thermometry in agricultural research and management obviates the necessity of users being cognizant of the instrument's target area characteristics. In this note, we illustrate the target dimensions when an infrared thermometer of specified field of view (4°, 8°, and 20°) is used to remotely sense surface temperature of a leaf, canopy, or crop surface. Knowledge of target dimensions and special characteristics related to the ellipse center and target point at various distances to and angles above the target surface should decrease error in surface temperature measurements and assist in standardization of techniques.

Additional index words: **Remote sensing, Canopy temperature.**

The use of handheld instruments to remotely measure the surface temperature of leaves, foliage, canopy, and crops has numerous applications in agricultural research and management: studies on crop energy balance (Jackson et al., 1981); irrigation timing and estimates of evapotranspiration (Clawson and Blad, 1982; Hatfield et al., 1983) and selection of breeding lines for water use characteristics (Mtui et al., 1981) and response to water deficits (Blum, 1980).

Routine use of the handheld infrared thermometer (IRT) to accurately measure the leaf, foliage, canopy, or crop temperature requires that the user be able to estimate target dimensions based on the position of the sensor in relation to the surface being remotely sensed (Fig. 1). This note illustrates how the field of view (FOV) of the infrared thermometer, distance to the target and viewing angle affect the shape and area of the target. We realize that the actual sensor in currently available commercial units is more rectangular than circular but have proceeded in this note with the assumption that the target dimensions are most conservatively estimated assuming the FOV is a solid angle.

The field of view of the IRT forms a right circular cone when it is held perpendicular to a surface. The view area is a circle of radius given by the following relationship.

$$r = f \tan\frac{FOV}{2},$$

where r = radius of the circle, f = distance of the view area from the instrument, FOV = field of view solid angle (Jackson et al., 1980).

Imaginary lines of sight lying on the outermost portion of this right circular cone are called generators of

[1] Contribution from the Agronomy Dep., Int. Rice Res. Inst., Los Baños, Laguna (mail address: P.O. Box 933, Manila), Philippines. Received 5 Sept. 1983. Published in *Agron. J.* 76:863–865.
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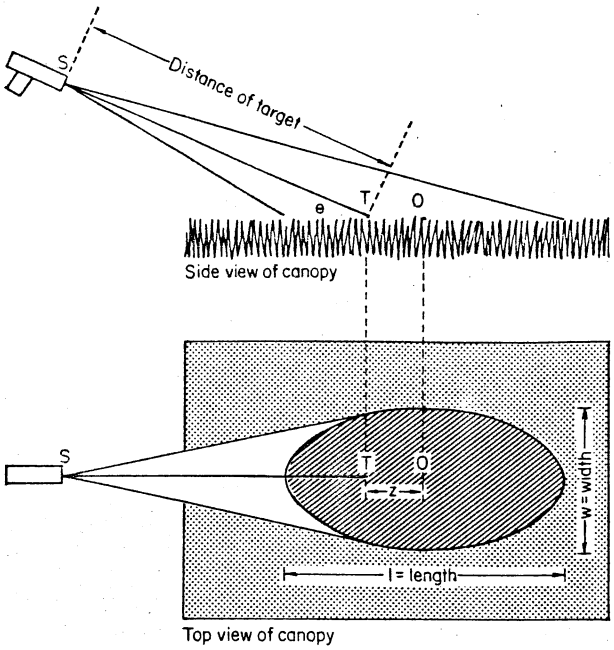

Fig. 1. Side and top view of the infrared thermometer viewing a crop canopy surface at a variable distance from the sensor (S) to the target point (T) and at a variable angle (θ) above horizontal with reference to the canopy height. The elliptical target area is described by its length (l) and width (w). Note the target point (T) is offset from the ellipse center by distance Z.

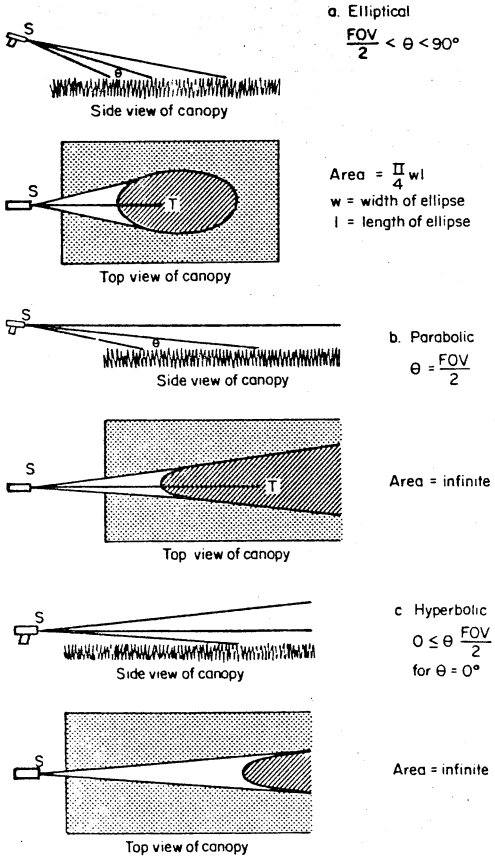

Fig. 2. Relationship between the infrared thermometer position (angle above horizontal) in relation to the canopy surface for three different conic sections a) elliptical, b) parabolic, and c) hyperbolic. Field of view is the instrument field of view, S is the sensor, θ is the view angle above the crop surface, and T is the target point.

the cone and they pass through the vertex S. The curves of the intersection of a plane and a right circular cone are known as conic sections. A conic section is the curve in which a plane cuts a right circular cone. When the IRT is held at a given angle above the horizontal

Table 1. The effect of distance to and viewing angle above the target surface on the dimensions of the elliptical area being remotely sensed. The three field of view (FOV) cases illustrated (4°, 8°, and 20°) are characteristic of currently available infrared thermometers.

Distance of target	Area length width offset	Viewing angle above the target surface 10°	20°	30°	40°
FOV = 4°					
0.50 m	A	0.006	0.003	0.002	0.002
	L	0.209	0.103	0.070	0.054
	W	0.036	0.035	0.035	0.035
	Z	0.021	0.005	0.002	0.011
1.00 m	A	0.023	0.011	0.008	0.006
	L	0.419	0.206	0.140	0.109
	W	0.071	0.070	0.070	0.070
	Z	0.042	0.010	0.004	0.002
2.00 m	A	0.094	0.045	0.031	0.024
	L	0.837	0.412	0.280	0.218
	W	0.143	0.140	0.140	0.140
	Z	0.083	0.020	0.009	0.005
3.00 m	A	0.211	0.102	0.069	0.054
	L	1.256	0.618	0.421	0.327
	W	0.214	0.211	0.210	0.210
	Z	0.124	0.030	0.013	0.007
4.00 m	A	0.375	0.182	0.123	0.096
	L	1.675	0.824	0.561	0.435
	W	0.285	0.281	0.280	0.280
	Z	0.166	0.040	0.017	0.009
FOV = 8°					
0.50 m	A	0.029	0.012	0.008	0.006
	L	0.478	0.212	0.142	0.110
	W	0.076	0.071	0.070	0.070
	Z	0.095	0.020	0.009	0.005
1.00 m	A	0.114	0.048	0.031	0.024
	L	0.956	0.425	0.284	0.219
	W	0.152	0.143	0.141	0.140
	Z	0.190	0.041	0.017	0.009
2.00 m	A	0.457	0.190	0.126	0.097
	L	1.911	0.849	0.568	0.438
	W	0.305	0.285	0.282	0.281
	Z	0.379	0.082	0.034	0.018
3.00 m	A	1.029	0.428	0.283	0.217
	L	2.867	1.274	0.852	0.657
	W	0.457	0.428	0.423	0.421
	Z	0.569	0.122	0.052	0.027
4.00 m	A	1.830	0.760	0.503	0.386
	L	3.823	1.698	1.136	0.876
	W	0.609	0.570	0.564	0.561
	Z	0.758	0.163	0.069	0.037
FOV = 20°					
0.50 m	A	∞	0.107	0.057	0.041
	L	∞	0.674	0.389	0.287
	W	–	0.202	0.185	0.180
	Z	–	0.163	0.059	0.030
1.00 m	A	∞	0.427	0.226	0.163
	L	∞	1.347	0.779	0.574
	W	–	0.403	0.370	0.361
	Z	–	0.326	0.119	0.060
2.00 m	A	∞	1.706	0.905	0.650
	L	∞	2.695	1.556	1.148
	W	–	0.806	0.741	0.721
	Z	–	0.653	0.238	0.121
3.00 m	A	∞	3.839	2.036	1.464
	L	∞	4.042	2.334	1.722
	W	–	1.209	1.111	1.082
	Z	–	0.979	0.356	0.181
4.00 m	A	∞	6.825	3.620	2.602
	L	∞	5.388	3.111	2.296
	W	–	1.613	1.481	1.443
	Z	–	1.305	0.475	0.241

over a plant canopy (assumed flat), the view area on that canopy assumes one of three particular conic sections: ellipse; parabola; and hyperbola (Fig. 2). When the angle θ is small resulting in a parabolic or hyperbolic conic section the sensor field of view extends past the desired target or plot canopy surface area. This condition leads to errors in surface temperature measurement by including in the sensor's view adjacent canopy or soil area outside the desired target in the first case and cool sky area in the second case. Orientation of the sensor so that an elliptical conic section cuts the canopy surface plane and its length and width are confined to the plot desired is the optimal relationship.

When $\theta = 90°$, the view area is a circle, a special form of ellipse when $w = l$. In the case where FOV/$2 < \theta < 90°$, for a constant target distance f, at greater angles, the elliptical shape tends to become circular and the area smaller.

At smaller angles and constant target distance f, the area becomes larger. In addition to θ, the distance to the target point also affects the ellipse dimensions. If the instrument is held further from T, the target point, while keeping θ constant, the view area becomes progressively larger by the relationship that the target area is proportional to the square of the distance to the target. Incorrect estimation of the ellipse area with increasing distance to the target point may result in systematic errors especially when the IRT is used to monitor surface temperature of small plots.

The derivation of the formulae for an elliptical view area with varying target angle (θ), target distance (f), and IRT field of view was obtained using Kells and Stotz (1949) and Purcell (1978)[3]. Table 1 illustrates the change in target dimensions and ellipse area being sensed when the IRT is held at various combinations of distance from and angle to the target. It should be noted in Fig. 1 that the target point aimed at is not the center of the ellipse being remotely sensed but is offset from the ellipse center by a distance Z. Table 1 gives the ellipse area, length, width, and distance Z for IRTs with 4°, 8°, and 20° FOV. As the instrument FOV increases the user's knowledge of Z becomes more important in accurately sensing the desired target surface temperature. For additional information on the effects of angle to the target on canopy surface temperature measurement see Kimes (1980).

[3] Full details of the formulae derivation with complete illustrations may be obtained upon request from the authors.

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LETTERS TO THE EDITOR

Dear Editor,

RE: SUNFLOWER POPULATION[1]

My letter (6) in response to Dr. Prunty's article on sunflower population (3) was confined to correcting an incorrect statement of fact (We did not use the head method described in his article) and correcting a misleading statement about our results (8 of our 12 experiments did not support his hypothesis). Dr. Prunty initiated more controversy in his latest article (4) to which I will respond. He now calls the head method the "100% stand" method, but continues to link our "100% stand" method and his "100% stand" method which are not the same as indicated in my letter (6). His "100% stand" method (3, 9) is potentially biased because judgment is involved in selecting heads for harvest. Consequently, his area method is better than *his* "100% stand" method.

Dr. Prunty used his *area* method to establish and harvest plant population densities at two locations (4). Yield differences among populations were not significant in either trial, but he gave neither coefficient of variation (CV) nor least significant difference (LSD) values. Consequently, the reader is uninformed of the variability, and cannot evaluate whether or not the data were too variable to justify a conclusion on population effect. However, he chose one location and calculated what the yields would have been if corrected to 100% stand, and these amounted to 190, 197, 204, and 205 g m^{-2} from 3.8, 5.0, 6.1, and 7.3 plants m^{-2}, respectively. He used this calculation to support his hypothesis that the "100% stand" method is biased because yield increased with population increases. I chose the other location and from his Table 1 and Fig. 1 calculated yields of 244, 241, 248, and 252 g m^{-2} from 5.0, 6.1, 7.5, and 9.1 plants m^{-2}, respectively. These small differences in nonsignificant data at both locations are not valid support of his hypothesis. However, these calculations are agronomically invalid because they ignore reduced plant competition! Loss of stand during the growth of the crop may be partially or fully offset by increased production from the remaining plants (2). Furthermore, the lowest population at both locations was adequate for maximum yield, so mathematically adding yields from nonexistent heads should increase calculated yields in direct proportion to the proportion of missing heads.

I do not know why our article (8) on uniformity of plant spacing was discussed. Despite its title, Dr. Prunty's paper (4) presented no data on how either soil water or plant population influence *uniformity of stand.* However, the second paragraph on p. 748 starts with two sentences about our research and the third sentence starts with, "This work shows. . . ." It should be corrected to, "My (Prunty's) work shows. . . ."

[1] Contribution from the Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, St. Paul, MN 55108. Paper no. 13,810 of the scientific journal series, Minnesota Agric. Exp. Stn. Received 27 Feb. 1984. Published in *Agron J.* 76:865–866.

APPENDIX I

Calculating the spot size of an IRT

F_2 = (FOV/2) The IRT in the Scheduler™ has an 8^o FOV at the extremes, about 6^o FOV at the half power points.

H = Height of IRT above the crop canopy

D = Horizontal distance from the IRT to the target.

S = Short axis of the spot size. The distance from the target back toward the observer to the edge of the FOV.

L = Long axis of the spot size. The distance from the target away from the observer to the edge of the FOV.

K = Indicator of whether or not sky is seen. If K is positive, no sky is seen. If K is negative, sky is seen. If K is between -1 and 0, the error is probably small. For calculation purposes, if K is less than 0.001, set K=0.001, or the trigonometric functions used will blow up. If K is less than -1, the IRT readings will be seriously biased by sky temperature.

W = Maximum width of the spot size

Calculations

All trig functions are in degrees. The example given is for a FOV of 6^{o}, height of 4 ft. and target distance of 25 ft.

*F_2 = FOV/2

1) $Z = (D^2 + H^2)^{1/2} = (16 + 625)^{1/2} = 25.3$

2) $G = \text{Sin}^{-1}\left(\frac{D}{Z}\right) - F_2 = \text{Sin}^{-1}\left(\frac{25}{25.318}\right) - 3 = 77.9$

3) $C = 90 - F_2 - G = 9.09$

4) $S = \frac{Z \sin(F_2)}{\sin(G + 90)} = 6.3$ ft.

5) $K = 90 - G - 2F_2$, If $K < 0.001$, then $K = 0.001$
If $K < O$, Then "sky is seen"
If $K < -1$, Then "Do not use at this angle"
For this example, $K = 6.1$

6) $L = \frac{Z \text{ Sin } (F_2)}{\text{Sin } (K)} = 12.5$ ft.

7) T = TOTAL length of spot size = L + S
= 18.8

8) $W = 2 Z \tan(F_2) = 2.6$ ft.

9) Total area viewed = 3.14159 TW/4
= 39.2 $ft.^2$

Fig. 1. Side View

$T1 = \frac{1}{2}$ of the angular field of view

1) $x = \sqrt{D^2 + H^2}$

2) $G = \sin^{-1}\left(\frac{D}{x}\right) - T_1$

3) $C = 90 - T_1 - G$

4) $S = \frac{\sin(T_1) \cdot x}{\sin(G + 90)}$

5) $K = 90 - G - 2 \cdot T_1$

6) $L = \frac{\sin(T_1) \cdot x}{\sin(K)}$

7) $L + S$ = Total Length of Field of View

Note: IF $K < 1°$, Set $K = 1°$

$L + S = 32.65 + 37.55 = 70.2$ cm

example: Instrument field of view = 4°, $T_1 = 2°$

$D = 400$ cm $H = 200$ cm

$x = \sqrt{400^2 + 200^2} = 447.2$ cm

$G = \sin^{-1}\left(\frac{400}{447.2}\right) - 2.0 = 61.44°$

$C = 90 - 2.0 - 61.44 = 26.56°$

$S = \frac{\sin(2.0) \cdot 447}{\sin(90 + 61.44)} = 32.65$

$K = 90 - 61.44 - 2.(2.0) = 24.56$

$L = \frac{\sin(2.0) \cdot 447.2}{\sin(24.56)}$

$L = 37.55$ cm

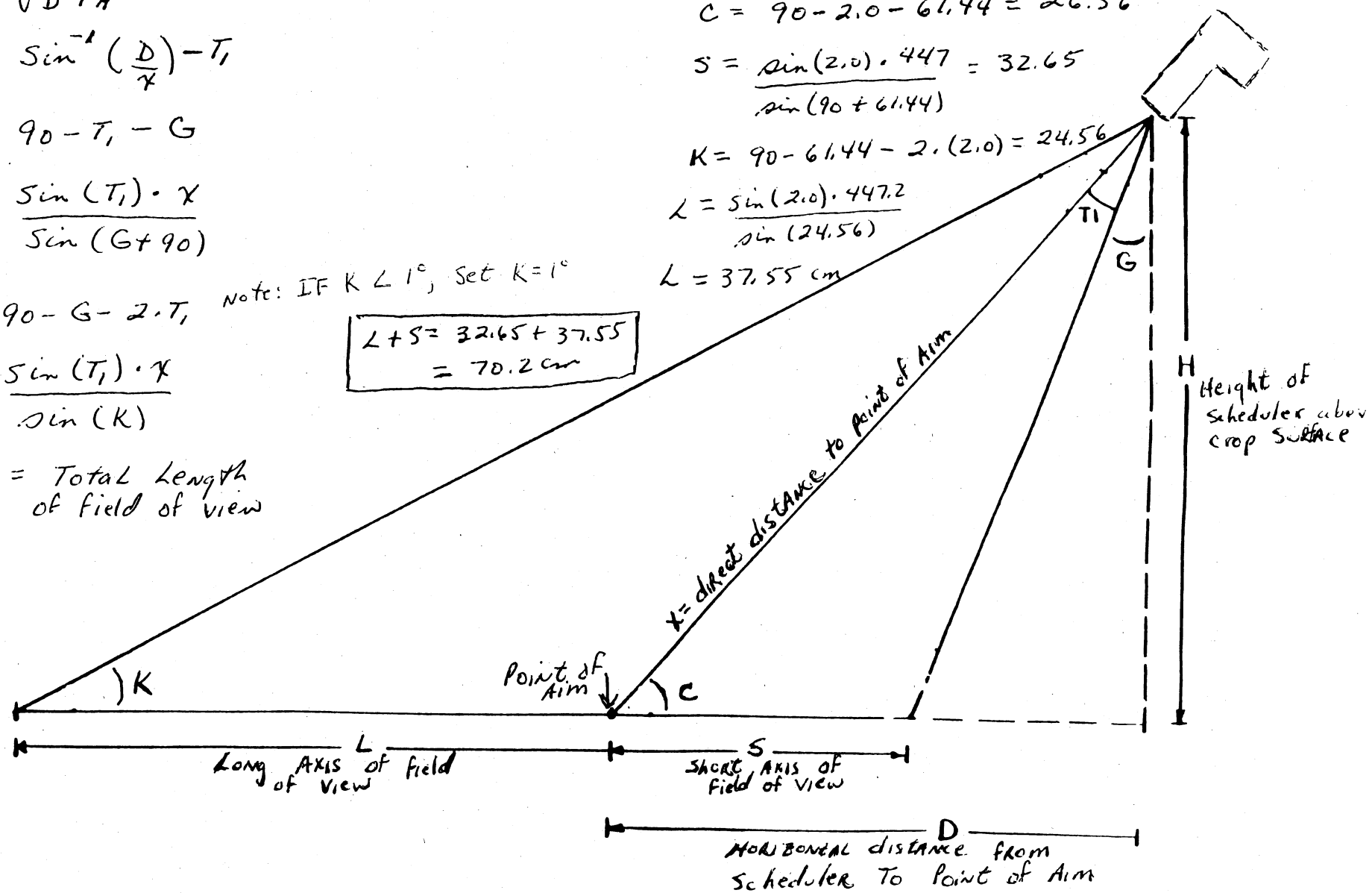
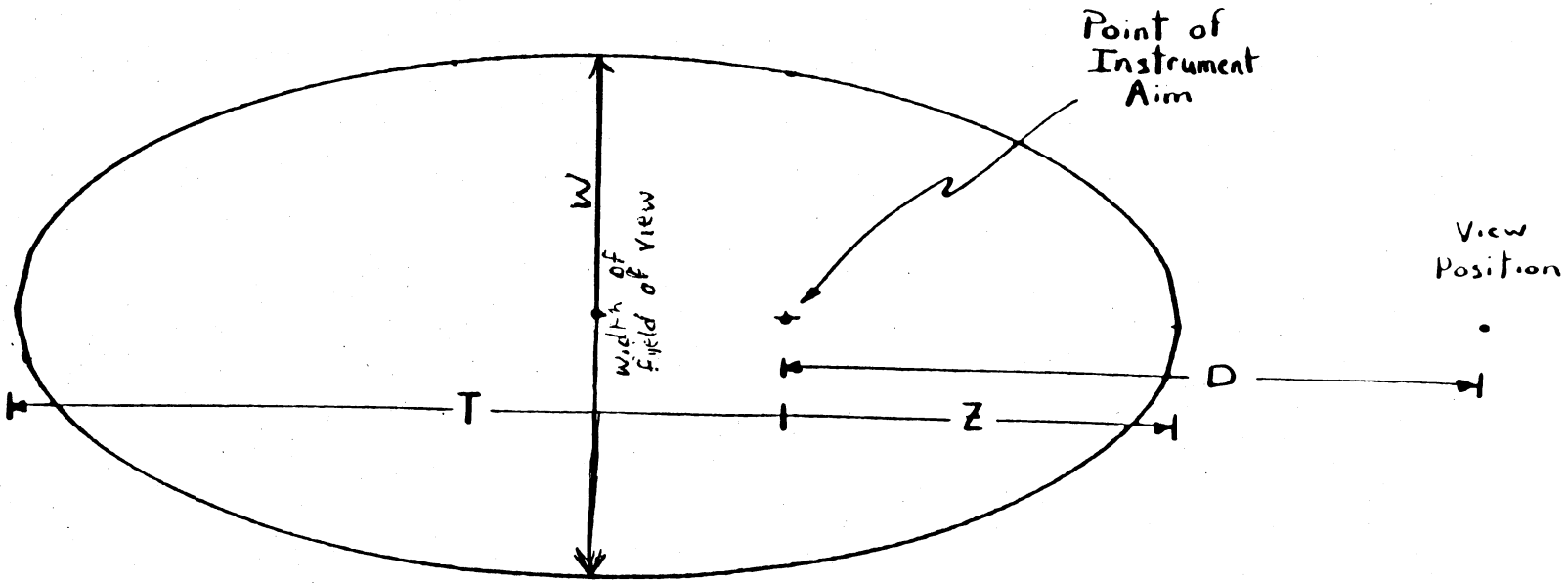


Fig. 2. Top View

8) $W \cong 2 \cdot X \cdot \tan(T_1)$

(example) $W \cong 2 \cdot 447.2 \cdot \tan(2°)$

$W \cong 31.2$ cm



Source:
David Nielsen
USDA
AKron, Colorado

Fig. 1. Side View

$T_1 = \frac{1}{2}$ of the angular field of view

1) $x = \sqrt{D^2 + H^2}$

2) $G = \sin^{-1}\left(\frac{D}{x}\right) - T_1$

3) $C = 90 - T_1 - G$

4) $S = \frac{\sin(T_1) \cdot x}{\sin(G + 90)}$

5) $K = 90 - G - 2 \cdot T_1$

Note: IF $K < 1°$, Set $K = 1°$

6) $L = \frac{\sin(T_1) \cdot x}{\sin(K)}$

7) $L + S$ = Total Length of field of view

Example: Instrument field of view $T_1 = 2°$

$D = 400$ cm $H = 200$ cm

$x = \sqrt{400^2 + 200^2} = 447.2$ cm

$G = \sin^{-1}\left(\frac{400}{447.2}\right) - 2.0 = 61.44°$

$C = 90 - 2.0 - 61.44 = 26.56°$

$S = \frac{\sin(2.0) \cdot 447}{\sin(90 + 61.44)} = 32.65$

$K = 90 - 61.44 - 2.(2.0) = 24.56$

$L = \frac{\sin(2.0) \cdot 447.2}{\sin(24.56)}$

$L = 37.55$ cm

$L + S = 32.65 + 37.55 = 70.2$ cm

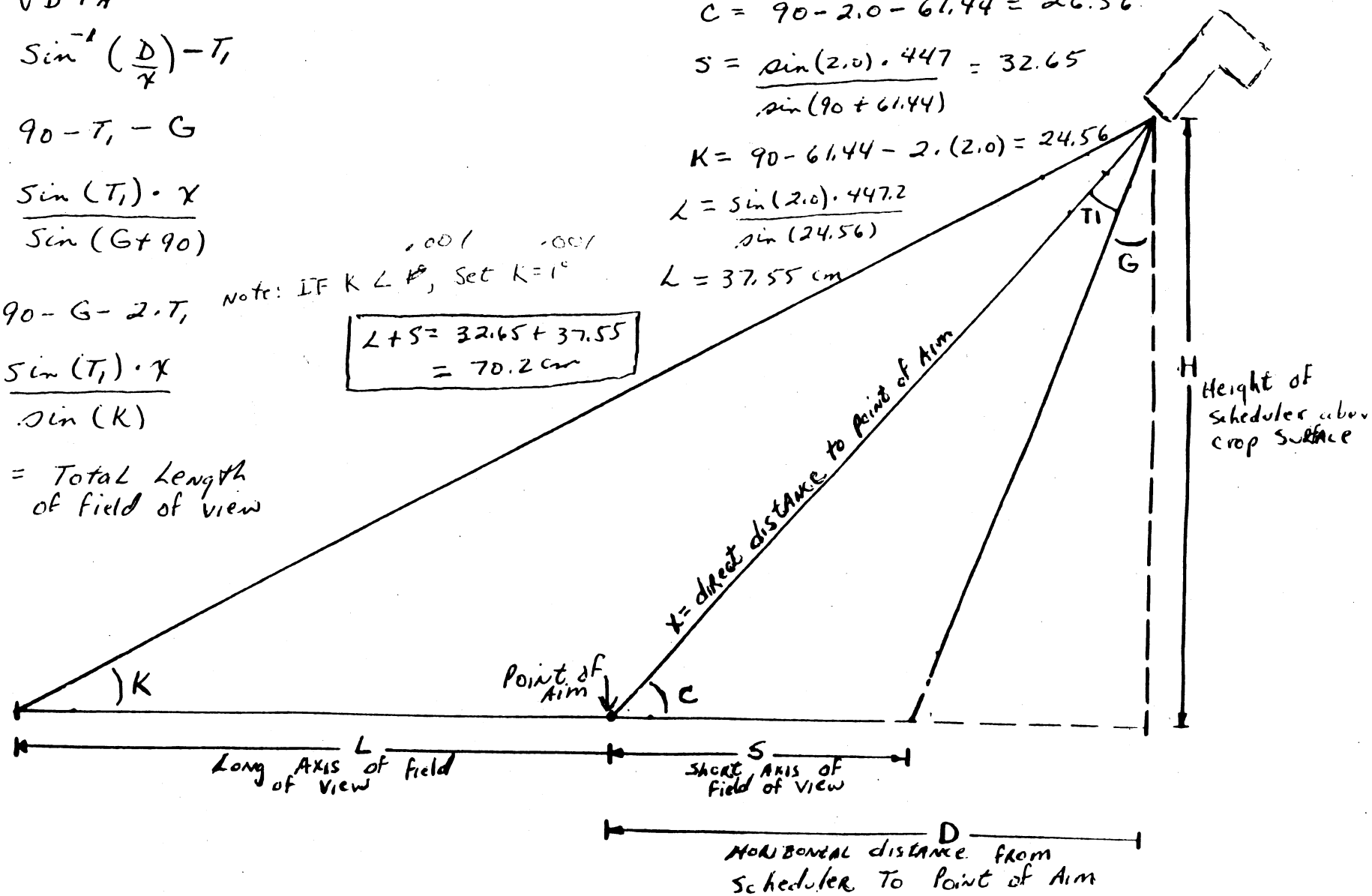


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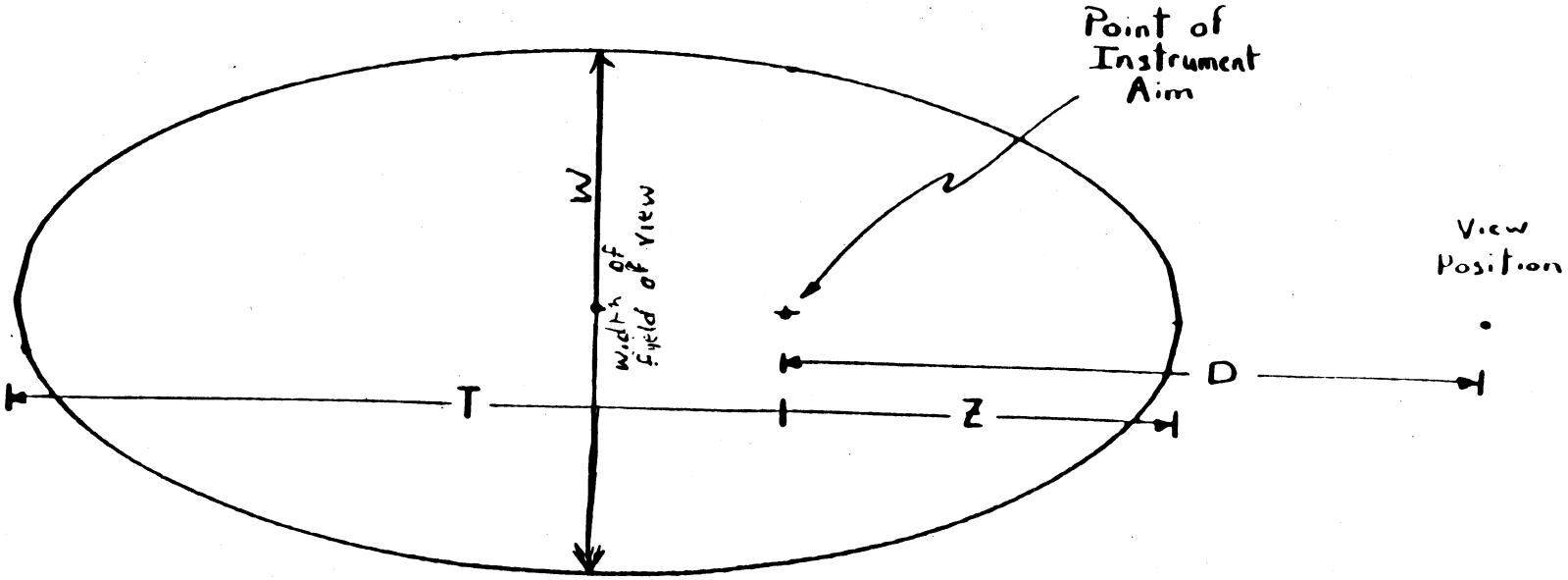
Fig. 2. Top View

8) $W \cong 2 \cdot X \cdot TAN(T_1)$

(example) $W \cong 2 \cdot 447.2 \cdot Tan(2°)$

$W \cong 31.2$ cm



Source:
David Nielsen
USDA
AKron, Colorado

THE STATIC EQUATION FOR THE IRT IS:

TDE=29.19715611*V-2.81682940*V*V+0.27688208*V*V*V;
IRT=TD+TDE;
STATIC=-0.662203+0.54889654*IRT+0.47212242*TD +15.33622049*V-0.07010936*V*IRT;

THE DYNAMIC TERM IS BASED ON:
DT=(TD(t)-TD(t-90))/90

DYNAMIC=STATIC-282.204*DT;

TD=DETECTOR TEMPRATURE (C)
V =DETECTOR OUTPUT VOLTAGE (VOLTS)
TDE=ESTIMATE OF DIFFERENCE IN TEMPRATURE BETWEEN TD AND TARGET TEMERATURE
IRT=INITIAL ESTIMATE OF STATIC TEMPERATURE
STATIC=FINAL ESTIMATE OF STATIC TEMPERATURE
DT=RATE OF CHANGE OF DETECTOR TEMPERATURE IN C/SEC (OVER A 90 SECOND INTERVAL)
DYNAMIC=FINAL EQUATION FOR ESTIMATING BLACKBODY TEMPERATURE

Resistance = ~~(Resistance)/1000~~ $\frac{(\text{Counts} * 5)}{8000 - C}$

LResis = log (Resistance/1000)

Temp = 122.096 − 33.67744 * LResis + 1.503759 * LResis^2

= 121.9732 − 33.67242952 LRes + 1.51620941 LRes^2

= 125.291836 − 36.958291 LR + 2.5376118 LR^2 − 0.1039252 7 LR^3

Fig. 1. Side View

$T_1 = \frac{1}{2}$ of the angular field of view

1) $\chi = \sqrt{D^2 + H^2}$

2) $G = \sin^{-1}\left(\frac{D}{\chi}\right) - T_1$

3) $C = 90 - T_1 - G$

4) $S = \frac{\sin(T_1) \cdot \chi}{\sin(G + 90)}$

5) $K = 90 - G - 2 \cdot T_1$ Note: IF $K < 1°$, Set $K = 1°$

6) $L = \frac{\sin(T_1) \cdot \chi}{\sin(K)}$

7) $L + S$ = Total Length of Field of View

Example: Instrument Field of View = 4°, $T_1 = 2°$

$D = 400$ cm $H = 200$ cm

$\chi = \sqrt{400^2 + 200^2} = 447.2$ cm

$G = \sin^{-1}\left(\frac{400}{447.2}\right) - 2.0 = 61.44°$

$C = 90 - 2.0 - 61.44 = 26.56°$

$S = \frac{\sin(2.0) \cdot 447}{\sin(90 + 61.44)} = 32.65$

$K = 90 - 61.44 - 2 \cdot (2.0) = 24.56$

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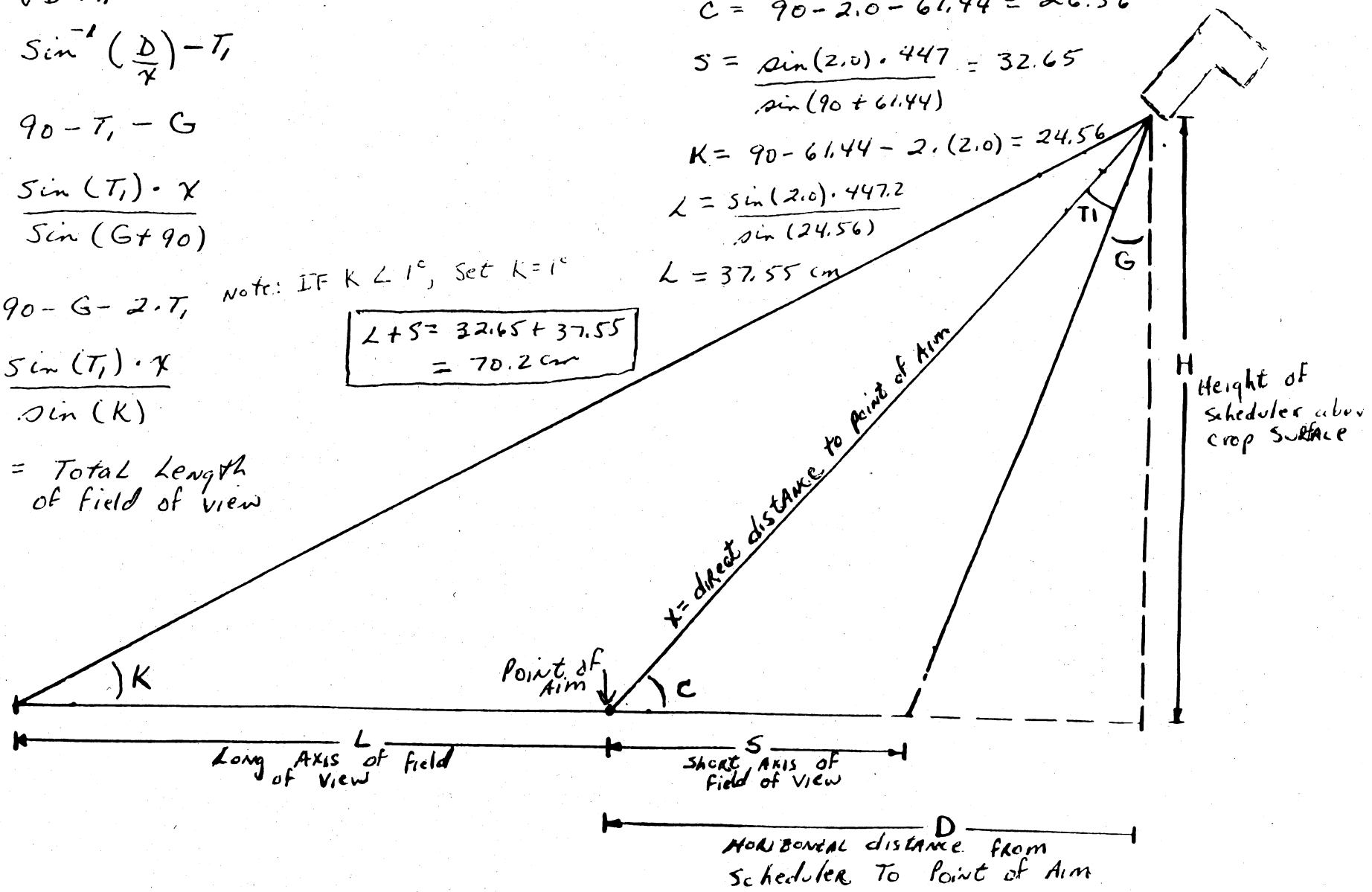
$L + S = 32.65 + 37.55 = 70.2$ cm



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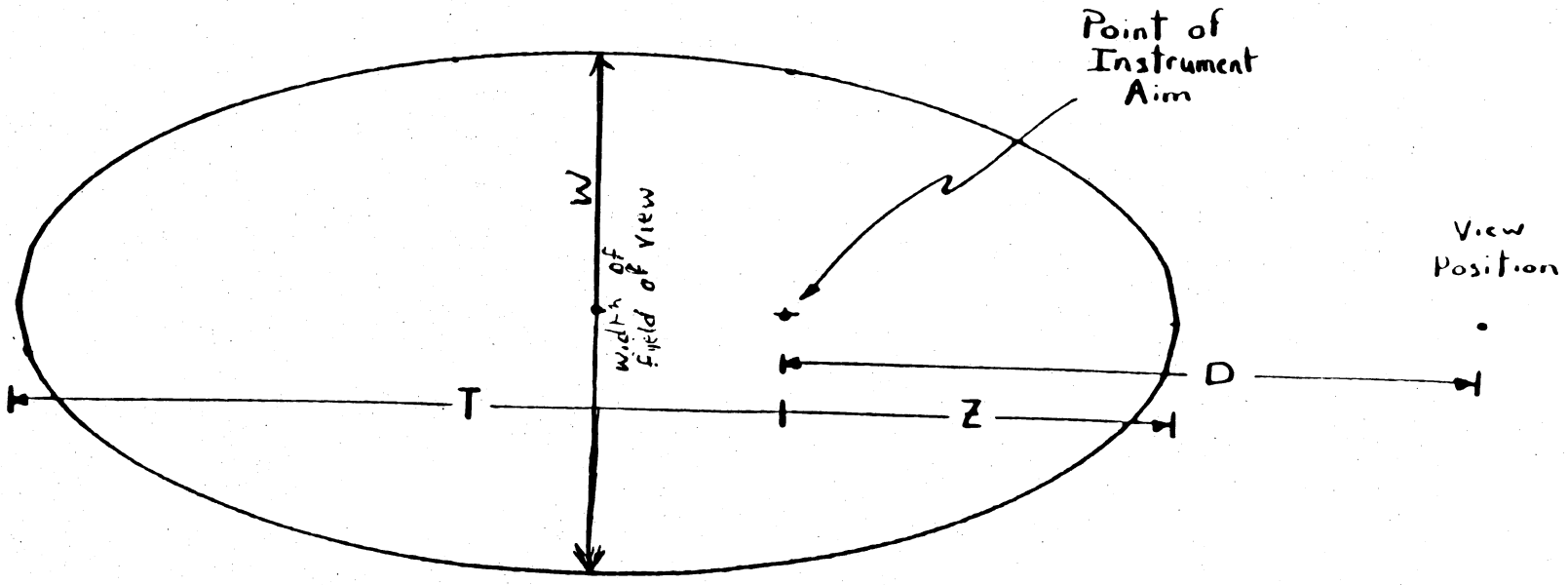

Source:
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APPENDIX I

Calculating the spot size of an IRT

F_2 = (FOV/2) The IRT in the Scheduler™ has an 8^o FOV at the extremes, about 6^o FOV at the half power points.

H = Height of IRT above the crop canopy

D = Horizontal distance from the IRT to the target.

S = Short axis of the spot size. The distance from the target back toward the observer to the edge of the FOV.

L = Long axis of the spot size. The distance from the target away from the observer to the edge of the FOV.

K = Indicator of whether or not sky is seen. If K is positive, no sky is seen. If K is negative, sky is seen. If K is between -1 and 0, the error is probably small. For calculation purposes, if K is less than 0.001, set K=0.001, or the trigonometric functions used will blow up. If K is less than -1, the IRT readings will be seriously biased by sky temperature.

W = Maximum width of the spot size

Calculations

All trig functions are in degrees. The example given is for a FOV of 6^{o}, height of 4 ft. and target distance of 25 ft.

*F_2 = FOV/2

1) $Z = (D^2 + H^2)^{1/2} = (16 + 625)^{1/2} = 25.3$

2) $G = \text{Sin}^{-1}\left(\frac{D}{Z}\right) - F_2 = \text{Sin}^{-1}\left(\frac{25}{25.318}\right) - 3 = 77.9$

3) $C = 90 - F_2 - G = 9.09$

4) $S = \frac{Z \sin(F_2)}{\sin(G + 90)} = 6.3$ ft.

5) $K = 90 - G - 2F_2$, If $K < 0.001$, then $K = 0.001$
If $K < 0$, Then "sky is seen"
If $K < -1$, Then "Do not use at this angle"
For this example, $K = 6.1$

6) $L = \frac{Z \text{ Sin } (F_2)}{\text{Sin } (K)} = 12.5$ ft.

7) T = TOTAL length of spot size = L + S
= 18.8

8) $W = 2 Z \tan(F_2) = 2.6$ ft.

9) Total area viewed = 3.14159 TW/4
= 39.2 $ft.^2$

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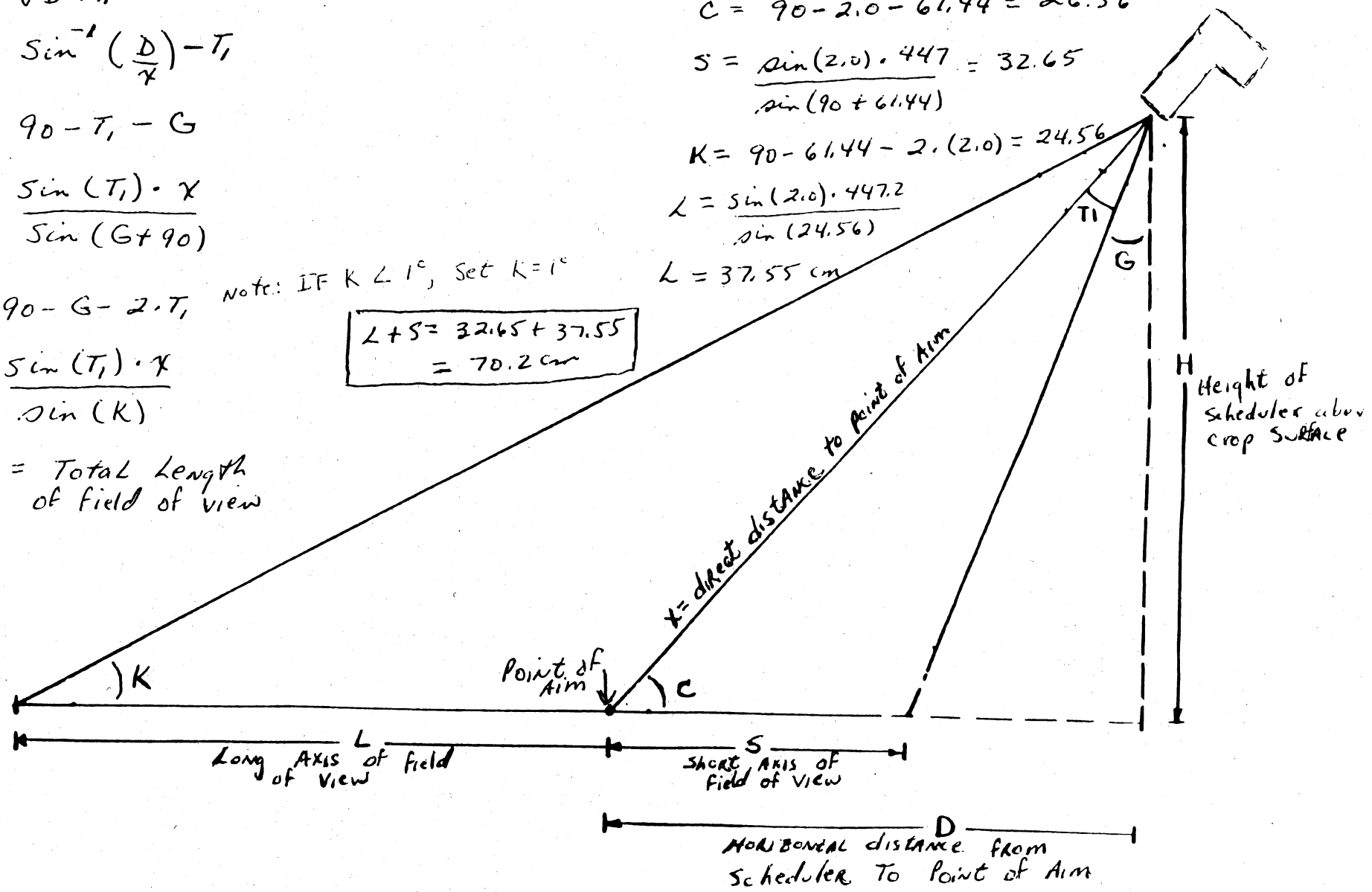

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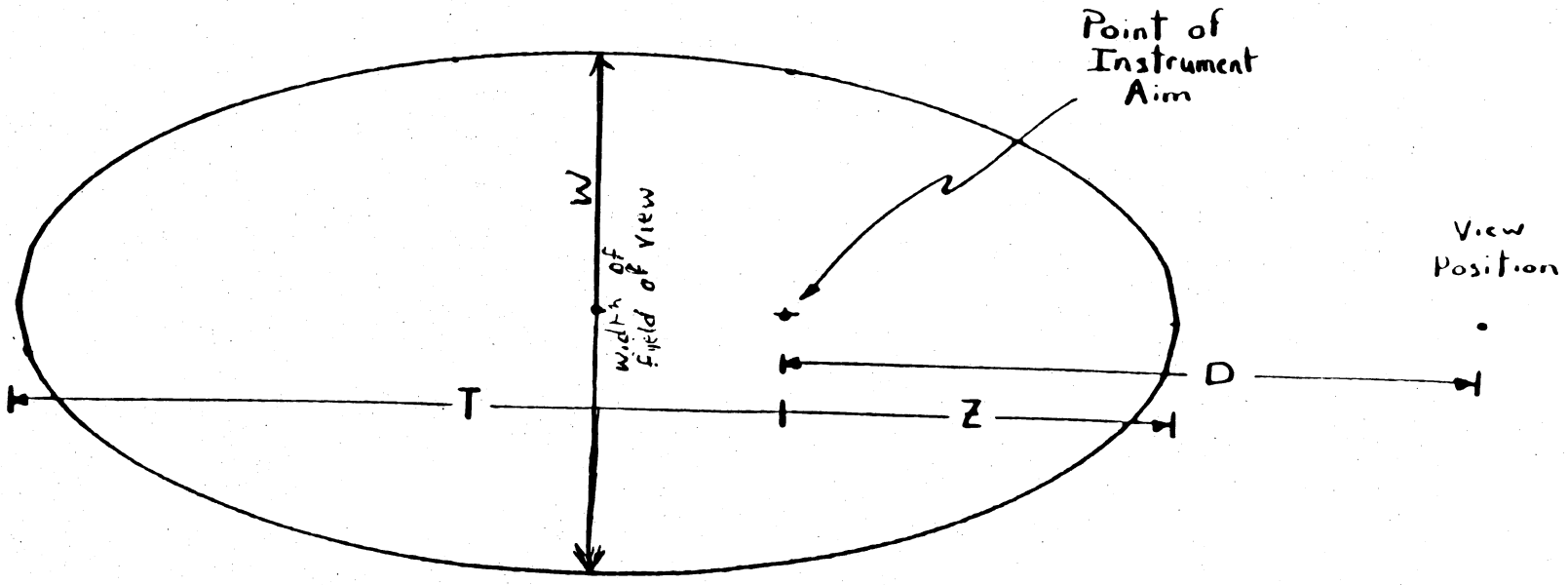

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